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Process improvement and BIM in infrastructure design projects – findings from 4 case studies in Finland

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<p>Building information modelling is increasingly adopted in today's infrastructure sector. However, the implementation of BIM in the design stage of construction projects and the benefits of BIM for design stage are not sufficiently studied. The adoption of BIM may call for changes in traditional design process. This research explores the current state of BIM implementation and design practice, and the possibilities for process improvement in the design phase of transport infrastructure lifecycle, by studying four case design projects in Finland.</p> <p>The data has been obtained in eight workshops with the members of the case project teams; in addition, preliminary interviews and a questionnaire survey have been conducted. The major revealed benefits of BIM are clash detection, cost estimation and machine control. However, the potential process benefits of BIM for design are not achieved. The study reveals a gap between BIM process and design process in the projects, and a knowledge gap between BIM experts and common designers. The major identified barriers towards achieving the higher level of BIM implementation are the inefficient information exchange, the lack of BIM skills and learning policies, and the lack of modelling guidelines and procedures.</p> <p>In addition, the work discusses the difficulties that have been encountered when attempting to carry out quantitative measurements in design projects, and proposes recommendations for those who plan to conduct such studies in future.</p>		
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Terms and abbreviations

BIM	Building Information Modelling
AEC	Architecture, Engineering and Construction – industry sector and activity
Infrastructure (projects)	In this work – transport infrastructure, particularly land transport
Lean	Philosophy of improvement in productive activities, originally developed in Japan
CE	Concurrent Engineering
Agile	A set of methodologies for managing software and product development projects
Collaboration model	A common model that integrates all discipline-specific data
Model coordinator (integrator)	A BIM-related role responsible for modelling supervision and integration of discipline data
Interoperability	Depending on the context: organisational interoperability and software interoperability
Initial design, conceptual design	The first, undetailed stage of design in construction projects
General design	The second, more detailed stage of design development in construction projects
Construction-level design	The last, most detailed stage of design development

1. Introduction

1.1. Background of the study

The rapid development of information and communication technology (ICT) since the second half of the last century has resulted in new challenges for businesses. So far, ICT has offered enormous advantages and ultimately changed the way businesses work; however, at the dawn of the ICT revolution these advantages were not as apparent as they seem today. Even nowadays, given the high number of information and communication solutions entering the market each year, it may sometimes become a difficult task for a company to decide if it should invest in acquiring a particular ICT product or not. Such investment does not exclusively relate to the offering itself, but also to the development of the necessary skills and process change in the company.

Since the early years of ICT adoption in industries, a body of research has formed to address the issues of exploring and evaluating the benefits of technology, and assessing the associated return on investment (ROI) (Mahmood & Mann, 1993; Weill, 1992; Davern & Kauffmann, 2000). To a large extent, the necessity of such studies was dictated by the fact that many businesses were hesitating in technology adoption, demanding a strong ‘proof’ of the benefits of technology. When the potential impact of technological advances on business activities and even the potential use of many technologies is unclear, making investment decisions is difficult. Even nowadays, the implementation of complex technologies and processes in growing companies can cause hesitation.

In today’s architecture, engineering and construction (AEC), the development of new information technology is largely related to Building Information Modelling (BIM), a set of technologies and processes for integrating and managing building information throughout the building lifecycle. The rapid technology adoption in the sector means that the companies have to face the problem of justifying their investments.

The concept of BIM includes a 3D modelling process, a related technology and also an information management approach. Unlike CAD solutions, BIM allows faster and more accurate modelling of structural elements and systems by using parametric object-based modelling technology, and supports integration of data in a single collaborative 3D model that can be used in construction and maintenance phases of life cycle (Eastman et al., 2008).

A commonly acknowledged benefit of BIM is detection of clashes between building elements that typically occur due to design inconsistencies and can result in major rework and cost in construction phase. Other benefits include modelling of construction site and coordination of construction work, accurate quantity take-off and cost estimation, 3D visualisation of buildings and support for collaboration between

different technical areas from design to operation phase (Eastman et al., 2008). The ultimate (and yet not completely achieved) goal of BIM is seamless integration of all building information to create a virtual building environment, so that the variety of building information is available for all users on all stages of building life cycle (Succar, 2009).

A number of studies call for quantifying the benefits of BIM and ROI related to BIM implementation, and development of metrics for measuring BIM performance, which are essential for setting organisational goals and evaluating the current state of BIM process (Succar, Sher and Williams, 2012; Coates et al., 2010; Mom and Hsieh, 2012; Barlish and Sullivan, 2012).

Barlish and Sullivan (2012) after analysing over 600 literature sources have identified only 21 studies that mentioned benefits of BIM explicitly. Only 4 studies contained empirical evidence derived from case study data. None of the studies provided methodology for calculating the return on investment (ROI) in BIM or comparing BIM and non-BIM projects. One of the likely reasons for lack of quantitative studies in this area is the fact that the companies most often do not collect extensive data on project performance that could allow developing reliable, if any, quantitative measurements.

In addition, a large share of possible benefits of BIM relate to the qualitative rather than the quantitative aspects of companies' performance. It can be difficult, if not impossible, to directly measure the impact of BIM on such abstract performance criteria as the quality of design solutions or the degree of mutual understanding between project stakeholders. Finally, reliable comparison between projects is difficult because each project is unique in terms of objectives, personnel, timescale, customer requirements, engineering difficulty and external environment. The lack of quantitative performance measurements is most noticeable in design and engineering activities because the performance criteria in these creative activities are difficult to formulate and quantify, and because the value of intangible outcome cannot be directly connected to resources or costs.

These difficulties in measurement relate to the inherent characteristics of services. Both BIM software solutions and architecture and engineering consultancy are services. The service characteristics include the intangibility of outcome and variations in process and resources due to customer involvement (Moeller, 2010).

To overcome the problems with direct measurement, the performance of services is frequently assessed indirectly through the perception of the clients, using various qualitative and quantitative approaches. The idea of measuring customer satisfaction to assess product quality is common in marketing and can be applied for both services and goods. There is a body of research that develops methods for measuring customer

satisfaction and perception of quality specifically for service industries, e.g. the SERVQUAL model (Parasuraman et al., 1985).

The approach of evaluating the perception rather than measuring the financial or process parameters is relevant to services within the AEC sector. Such exploration of perceptions can be focused on the qualitative benefits of ICT and process change, which may be hard to quantify. The study of perceptions can also provide the initial knowledge for developing direct, quantitative performance measurement in the future.

1.2. Research scope and objectives

The current research aims at exploring the perception of benefits of BIM and the process improvement in the design projects in transport infrastructure sector. Since the new technology typically requires companies to change their processes and work practices, the research examines the experts' vision of process change and organisational change and its relation to BIM implementation. It discovers challenges faced on the design phase of infrastructure projects, and examines the capability of BIM to become the enabler of collaborative design. The practical objective of the study is to provide recommendations for different industry stakeholders and to suggest directions for the future research.

According to the initial plan, the main objective of the research was to apply quantitative methods to understand the impact of BIM on project performance. However, the initial phase of the research revealed that, given the available data, achieving this goal was not possible. Neither of the available companies did collect sufficient data in their projects. In addition, the timeframe of the research did not permit to follow the entire projects, applying the right methodology from the beginning of the projects until the end, as required to make comprehensive measurements. As a result, the research objectives were reformulated. However, some recommendations on how to carry out the measurements in future are formulated in chapter 5 based on the experience gained during the study.

The research objectives can be summarised as following:

- Understand the factors that can make BIM beneficial for design
- Examine the current state of design practice and BIM implementation in different infrastructure projects, identify problems and opportunities
- Evaluate the perception of BIM and design process by the project teams
- Utilise the theoretical and practical knowledge to provide a framework for future BIM and design process development
- Provide recommendations for future research

The formulation of the research objectives leads to the following research questions. The first research question aims at discovering the theoretical concepts that could explain the factors of successful design. The question is mainly addressed in the literature review chapter.

RQ1. What process-related and organisational factors determine the efficiency and effectiveness of collaborative design in construction projects?

The second research question explores the potential role of technology in achieving better performance in design, based on the factors explored in the previous question. This question is addressed in both the literature study and the empirical study.

RQ2. What is the potential role of BIM and other technologies in maximising the efficiency and effectiveness of collaborative design in construction projects?

The third question evaluates the current state of process and technology in the industry based on the knowledge obtained when answering the questions 1 and 2. The current state of industry is examined in the empirical study. The third question relates to both the objective indicators of the industry's state and the perception of professionals, which plays a major role in this research.

RQ3. What is the current state of design practice and BIM implementation in the infrastructure sector in Finland? How do the professionals perceive it?

The last research question concerns the theoretical and practical implications of the results of the study, which are discussed in the last chapter.

RQ4. What actions can be taken by the design companies in infrastructure sector regarding the technological and process development in order to increase performance in design activities?

The research framework based on the research objectives and research questions is visualised on figure 1.

1.3. Research motivation

The choice of design phase of infrastructure lifecycle as the focus of this study is related to the low number of existing studies that could describe the use of BIM in actual design projects and could explore a connection between the potential benefits of BIM and design process change. The benefits of BIM on construction phase are generally explored better than benefits on design phase.

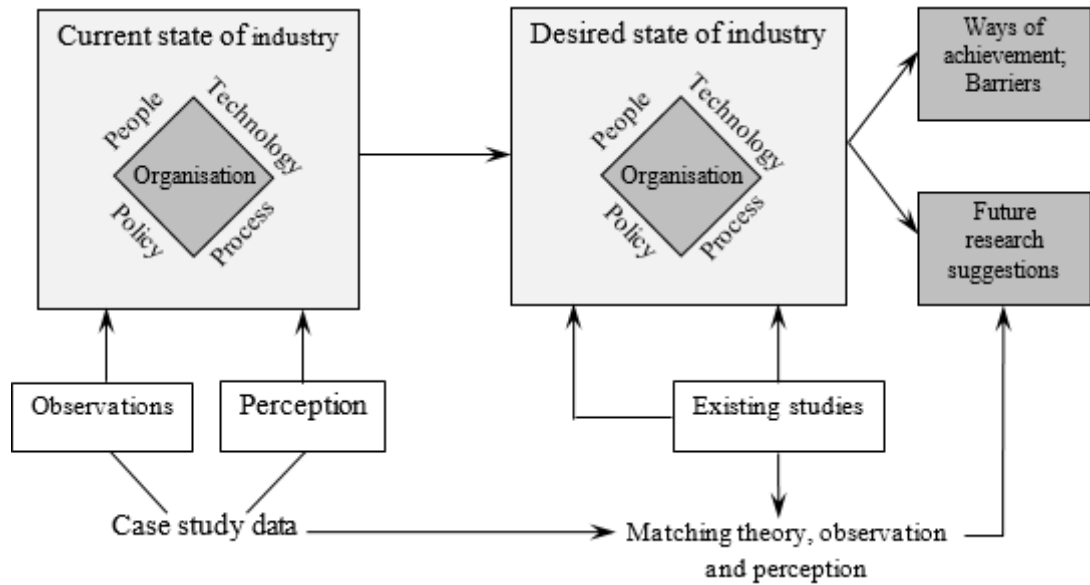


Figure 1: The research framework

At the same time, the design phase of lifecycle has a critical influence on building's performance and has the largest impact on lifecycle costs when compared to other phases (figure 2). In the end, it is architects and engineers who initially deliver BIM, and therefore the design companies must be able to feel the benefits of BIM.

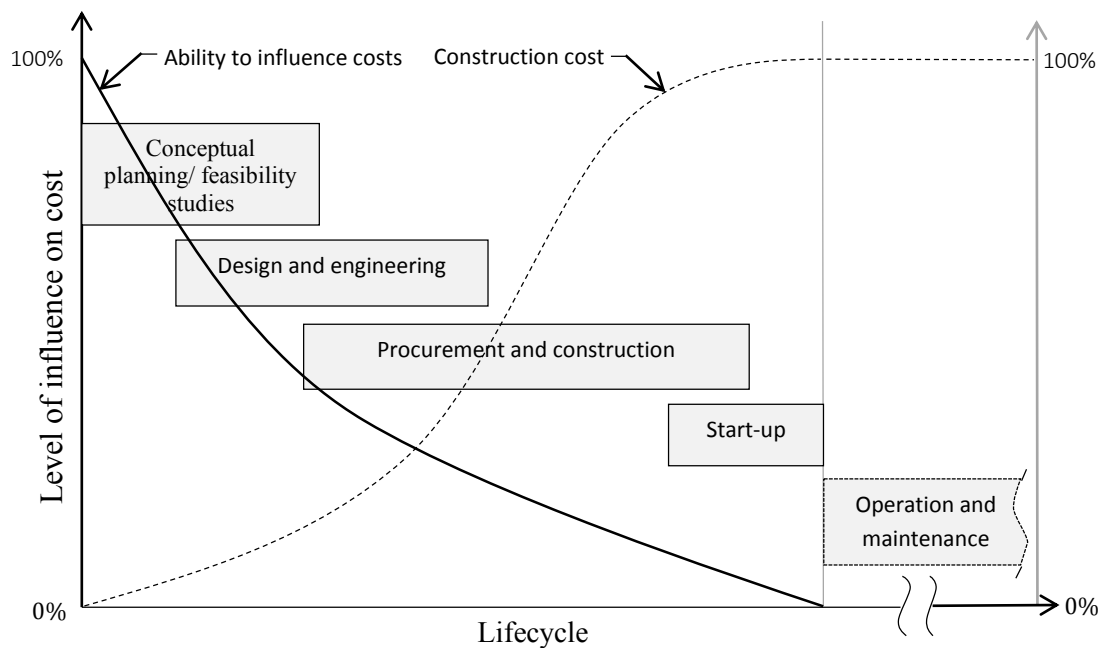


Figure 2: Influence of overall project cost over the project lifecycle. Adopted from Eastman et al., 2008: 99

The research is focused on infrastructure projects. Discussions with industry experts held before the research have suggested that the adoption of BIM in the infrastructure sector worldwide is behind the adoption in building sector. The literature review

undertaken as a part of this work has revealed that the implementation of BIM in infrastructure construction projects is not sufficiently studied.

The role of design process and focus on process in the study require a separate mention. The particular assumption about BIM to be investigated in this study is that it can facilitate the efficiency of design process through supporting collaboration and communication in design teams, particularly between different technical areas. The expectation is that BIM is most beneficial when implemented together with the right process, creating a sustainable synergy. The studies and expert opinions emphasise the connection between BIM implementation and process improvement.

A view of organisation as a socio-technical system commonly found in literature on Lean, often includes three dimensions: people, process and technology. These dimensions are outlined in a book on Toyota Product Development System by Morgan and Licker (2006), and are also present in BIM-related articles (e.g. Arayici et al., 2011). The study by Succar (2009) describes the implementation of BIM from the point of view of three nodes: technology, policy and process. Figure 3 combines them into four components of organisational performance: people, process, technology and policy.



Figure 3: The four components of organisation's performance: people, process, technology and policy

Although new technology can cause process change, the technology adoption should not be viewed as a primary or a more important concept compared to process improvement. It is important to note that this study, while exploring the relation between BIM and design process, will consider process improvement an independent conceptual entity. A variety of practices have been developed in AEC and other industry domains to maximise the effectiveness of designing in the existing circumstances and business environment. BIM and other technology can enhance or disrupt these practices, impact the efficiency of the design activity in a positive or a

negative way. The technological changes are calling for major shifts in conception of how design work should be carried out.

The research aims at exploring what practices support the efficiency and quality of design in a best way in the current circumstances and if the technology (not necessarily or only BIM) can enhance the positive impact of these practices. For example, the research investigates the potential application of data management tools and computer-aided project management and control in infrastructure design firms. It also investigates whether substantial change in design process would be needed in future to achieve the synergy between technology and process.

The design process in this research will be examined from the perspective of Lean philosophy. This set of approaches was initially developed by Japanese car manufacturers, but was later applied to other industries and activities. Lean philosophy aims at identifying and eliminating different types of waste that occur in business activities, in order to maximise value delivered to the customer. Any action, operation or time period where no value is added to the product constitutes waste and should be excluded from the process if possible.

The value and waste concepts are intuitively simple and close to how people understand efficiency. Lean methodology, nevertheless, is very comprehensive and includes a variety of practices applicable to different kinds of activities in different industries. The principles of Lean and their application to design process will be discussed in detail in chapter 3.

1.4. Research planning and the literature study

The research goals were addressed in two stages: (1.) literature study and (2.) empirical study. The literature study provided the basis for formulating the research questions and planning the empirical research. It was divided into two phases. The first phase included the initial exploration of the research field and the formulation of research objectives and questions. These questions and objectives were refined later during the research process. The majority of this phase's outcomes have been already presented in the first chapter.

The second phase of literature review addressed the research questions in detail, and was particularly focused on research questions 1 and 3:

RQ1. What process-related and organisational factors determine the efficiency and effectiveness of collaborative design in construction projects?

RQ2. What is the potential role of BIM and other technologies in maximising the efficiency and effectiveness of collaborative design in construction projects?

These general research questions were broadened during the literature review when the variety of topics addressing these questions was discovered within the literature, because none of the studies could answer the questions comprehensively.

Due to the lack of literature within the AEC field that could address the research questions, the review included a number of studies that could create a theoretical basis for process improvement in the sector but were not related to the AEC directly. This included the fundamental research on design ontology and cognition, innovation and knowledge management, communication, collaboration, lean and process improvement, information management, software engineering and product development. This was beneficial for the study because it allowed bringing the notions from different fields together and benchmarking the concepts.

This conceptual approach and the broad scope of research topics required a narrative and exploratory way of conducting the review. At the beginning of the study a list of questions and topics was prepared to define the directions of the search. Different combinations of search words related to those topics were then used to find the relevant scientific articles. The relevance of the articles was assessed according to the following criteria:

- Relevance to the search topic;
- Scope of the study: industry sector, location.
- Source of publication: the review considered only the articles published in journals and conference proceedings, published dissertations and books;
- Number of citations;
- Year of publication.

After the new topics emerged, the questions were refined and the search process reiterated. The relevant references cited in the literature were also examined. The search was conducted through Google Scholar and complemented by Aalto University Library and scientific publication databases, such as ScienceDirect. In addition, notable books and articles known prior to the study were reviewed.

The literature review is presented in chapter 2. Section 2.1 of the chapter provides general overview of BIM and AEC business environment. The later sections (2.2 – 2.4) describe the ontology and conceptual characteristics of collaborative design from managerial point of view, and explore the potential of applying lean approach to design practice. Section 2.5 discusses the potential benefits of ICT and particularly BIM for design stage of construction projects. The last section (2.6) is a brief summary of the conclusions and hypotheses formulated as the result of literature review, which have shaped the empirical study.

Chapter 3 describes the methodology of the study. Chapter 4 describes the case projects and presents the results of the empirical study. Chapter 5 includes the discussion of results, theoretical and practical implications. The sequence of the research process is illustrated on Figure 4.

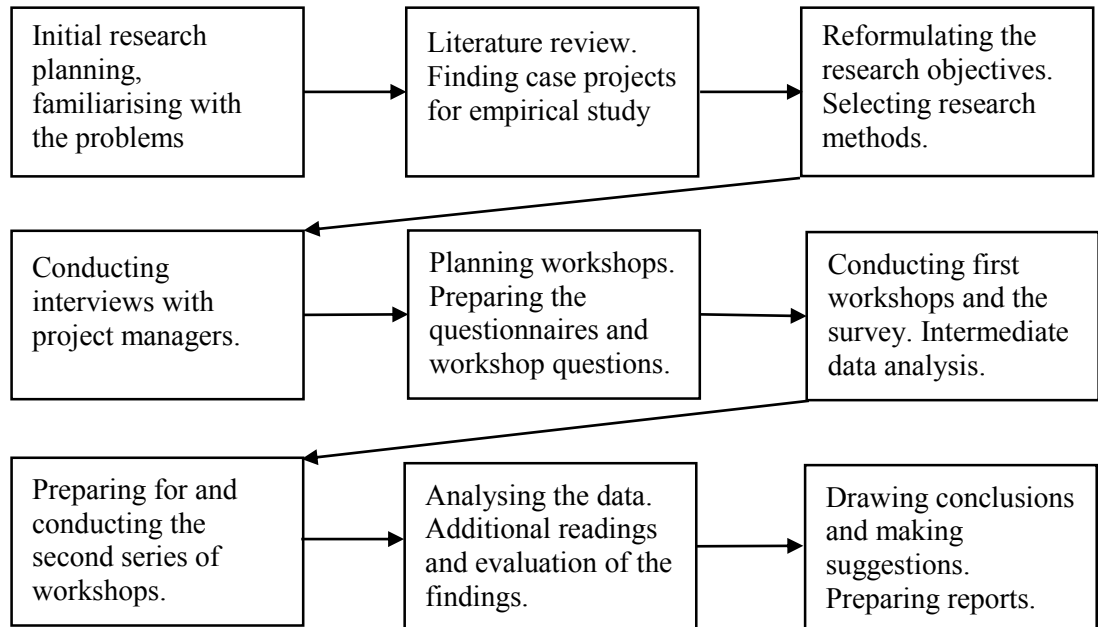


Figure 4: The research process

2. Theoretical foundations

2.1. Overview of Building Information Modelling

According to Khanzode (2012), today's construction industry is characterised by high complexity, especially in highly technical facilities such as hospitals and data centres. This has led to high specialization and vast array of subcontractors and consultants in projects. The parties and disciplines include key trades (such as mechanical, engineering and plumbing - MEP) and auxiliary trades (glass and glazing, elevators, landscaping, pneumatic tubes etc.). According to statistics provided by Eastman et al. (2008: 9), sixty-five percent of construction firms consist of less than five people. At the same time, the average number of companies participating in a construction project is 420, and the average number of individuals involved is 850. The coordination of work of different parties on different stages of a project and the corresponding information exchange are complex and massive processes. The average number of pages of documents generated in a project is 56 000. (Eastman et al., 2008: 2-3)

According to numerous reports and studies, the productivity of construction sector is significantly behind other non-farm industries. The sector suffers from low level of

automation, low labour productivity and lack of productivity growth (Eastman et al., 2008: 8-10; Bergly, 2001; Aapaoja, 2014: 17).

Aapaoja (2014: 17) synthesises the relevant articles and suggests the following list of problems of the construction sector:

- the costs are finally accumulating to the customer,
- major deficiencies in several different fields of know-how (e.g., design, quality, lead time, and predictability of work),
- differences (e.g., process, methods, viewpoints, opinions) between project organization and both internal and external stakeholders are not taken into account in the best possible way,
- functional decentralization and inefficiency,
- inability to collaborate,
- lack of processes to transfer and develop the knowledge and competencies, and
- harsh sub-optimization during the project

The approach to managing construction information traditional in AEC is characterised by inefficiency. During the design phase of construction projects, each design discipline creates its own set of engineering documents to be provided along with typically less detailed general documents. This documentation is passed forward to the subsequent designers and then to a building contractor. In building construction, there are also subcontractors who create detailed construction-level documentation within their own technical areas. (Eastman et al., 2008: 4-6)

Because of high number of participants and differences in standards, the construction-level documentation is prone to mistakes and inconsistencies. These mistakes and inconsistencies, if not identified prior to construction, can make construction companies delay their work and even rebuild some of the structures, which can significantly increase construction costs. In addition to errors, designs can require changes during construction due to unanticipated site conditions, changes in available materials and technologies, and new customer requirements. Clarification of design documents requires construction contractor and subcontractors to send requests for information (RFI) to designers, which can be very time-consuming. Incurred losses often result in legal disputes between project participants. (Eastman et al., 2008: 4-6)

The case studies conducted by Fulford and Standing (2014) suggests that high fragmentation in the industry, disparate project management processes and non-standardised information contribute to low productivity. As they summarise in the article,“(1.) *the construction industry lacks the ‘strength’ of relationships necessary to create a network of organisations that trust and have shared values; (2.) design processes should include both value engineering and lifecycle costing; (3.) procedures*

and information need to be standardised; (4.) there should be more emphasis on value adding project management activities.”

Building information modelling (BIM) has emerged from 2D and 3D CAD solutions in response to numerous problems and requirements specific to construction that were not addressed by CAD and paper-based information process (meaning both physical paper and its digital equivalents). Although the wide adoption of BIM has started within the last decade, the term has been known for almost 20 years, and the core principles of BIM were outlined as early as in 1975. (Eastman et al., 2008: xi)

BIM is a process of creating and managing the digital representations of building's spaces, elements and systems, including their spatial, functional, temporal and economic characteristics. Like 3D CAD, it represents the spatial characteristics of building's elements and surroundings in three-dimensional environment, making it possible to visualise the building in detail. (Eastman et al., 2008: 13)

The core technological difference of parametric object-based BIM from CAD is that BIM typically deals with meaningful objects, parameters and relationships between objects rather than pure geometric shapes and surfaces. Drawing the whole building with all its details manually in CAD is a difficult or sometimes impossible task, especially when frequent changes are required in drawings. BIM systems compute the models according to object rules and parameters set by a user, allowing automation of changes and automated checking for consistencies. (Eastman et al., 2008: 14)

The conceptually important aspect of BIM approach is that it aims at combining and centralising all construction drawings and data throughout the whole life cycle of a building. BIM can integrate all 3D models of different building systems and elements in a single virtual environment, called collaboration model or build model, and integrate other construction and engineering data in connection with different 3D objects in that model, including materials, cost and various technical details. Initial data that describes situation before the project, for example existing structures, terrain and surroundings, is also integrated in the model.

This approach gives a number of benefits to the project. The technology allows visualising the building and providing all companies involved in a project and all individual members of a project team with comprehensive and consistent data. To decision-makers, BIM gives additional support in formulating the requirements and choosing between alternative solutions. To designers, it can work as a collaboration tool helping to coordinate the work of different technical disciplines. It allows detection of errors and clashes in designs (e.g. clashes between pipelines and building foundations) early in the design phase. (Eastman et al., 2008: 16-21)

BIM can also facilitate comprehensive engineering calculations and construction cost calculations during design, as early as on conceptual design phase. Such systems can combine spatial 3D data and other construction and engineering data from different technical domains. (Eastman et al., 2008: 18; Sattineni & Bradford, 2011)

The shared 3D model helps the building contractor and subcontractors to coordinate their work on construction site and eliminate possible conflicts (Eastman et al., 2008: 19-20). Advanced BIM tools can model the temporal (4D) and economic (5D) characteristics of a building and building process, to create a visualised simulation of construction work with the corresponding schedule, material supply and cash flow calculations connected to the project's timescale. This is used for planning the construction work, including its financial and logistical aspects (Eastman et al., 2008: 18; Kang, Anderson and Clayton, 2007). After construction is finished, the models can facilitate efficient operation and maintenance (Eastman et al., 2008: 20-21). BIM is an intelligent approach to creation and handling of building information throughout the whole lifecycle of the building.

M. A. Mortenson Company's definition of BIM technology, cited in BIM Handbook (Eastman et al., 2008: 13), describes BIM as an "intelligent simulation of architecture", and gives the following definitive characteristics of such simulation:

- Digital
- Spatial (3D)
- Measurable (quantifiable, dimension-able, and query-able)
- Comprehensible (encapsulating and communicating design intent, building performance, constructability, and include sequential and financial aspects of means and methods)
- Accessible (to the entire AEC/owner team through an interoperable and intuitive interface), and
- Durable (usable through all phases of a facility's life).

Although this initial description of BIM is short and general, it provides some view on the potential impact of BIM on construction industry. The BIM Handbook states no current implementations of BIM meet all of the listed criteria (Eastman et al., 2008: 14).

The ultimate goal of BIM innovation, as it is often seen, is integration of all participants in a shared collaborative project delivery process, based on BIM. Succar (2009) divides BIM implementation in three capability stages, which are defined by minimum requirements that organisations have to meet in order to qualify for each stage:

1. **Object-based modelling** – organisation deploys an object-based modelling tool. On this stage BIM is only used within one organisation. An organisation produces models to enhance the quality of its work but the models are not transferred to other parties.
2. **Model-based collaboration** – organisation is involved in multidisciplinary model-based collaboration. On this stage several parties in the project use BIM and they are able to transfer data to each other.
3. **Network integration** – organisation shares object-based models with at least two other organisations. On this stage several parties share integrated models throughout the project, and their software is able to use the models and interchange data. This can be achieved using model server technology.

After network integration is achieved, the industry continues to develop to post-BIM stage, with ever-evolving goal of employing virtually integrated Design, Construction and Operation (Succar, 2009).

The literature provides the connection between the benefits of BIM and the use of relational project delivery arrangements. Traditional contracting arrangements, and particularly design-bid-build (DBB), are used in the largest share of today's construction projects and in up to 90% of projects in public sector (Eastman et al., 2008: 3-5), since some form of tender is typically required for public contracts by state legislations. The majority of projects in the infrastructure sector are public, and therefore this procurement method dominates the sector. In DBB, the design tasks, consultancy, construction work, maintenance and other tasks are contracted separately to individual parties not directly connected with each other by contractual relationships. This procurement method is usually based on the lowest bid. (Eastman et al., 2008: 4-7; Aapaoja, 2014: 17).

The traditional DBB approach suffers from numerous flaws. This contracting method does not allow involving subsequent design stakeholders in the early phase of the project, limits collaboration, information exchange, knowledge transfer and innovation (Eastman et al., 2008: 4-6; Aapaoja et al., 2013; Aapaoja, 2014; Matthews and Howell, 2005). In addition, the sequential work process favours point-based design – instead of optimising the overall value of the project, local optimisation occurs in different technical areas (Aapaoja, 2014: 17; Matthews and Howell, 2005). There is a tendency to rush over conceptual planning phase to detailed design and to construction in order to limit the costs, without proper understanding of project requirements and objectives, which can undermine the project's value. (Aapaoja, 2014: 17-18)

An implication of the traditional approach for information exchange is inefficient information flow caused by lack of interoperability. This is a large concern with regard to BIM implementation. A large variety of specialised modelling and engineering software exists that are not always interoperable with each other, which makes BIM

hard to extend over the building lifecycle and among the project participants. The study by the US National Institute of Standards and Technology (NIST) showed that inefficient interoperability accounted for a significant increase in construction costs (Gallagher et al., 2004, cited in Eastman et al., 2008). The key reasons for the cost increase as suggested by the study were (1.) redundant computer systems and inefficient business process, (2.) manual data re-entries and requests for information (RFI), and (3.) delay costs associated with idle employees and resources.

The adoption of Relational Project Delivery Arrangements (RPDA), in which all project participants are unified by a common contract, can become an important facilitator of productivity improvement in construction (Aapaoja, 2014; Lædre and Haugen, 2001). There is evidence that such arrangements result in cost savings in construction projects (Lædre and Haugen, 2001). Early stakeholder involvement and integration enhances value creation in projects. (Aapaoja et al., 2013; Aapaoja, 2014). Integrated project delivery arrangements that are based on collaboration and shared risks allow the achievement of BIM-based network integration (Succar, 2009).

The innovation in the AEC sector is fostered by the rising complexity of the buildings and increasing requirements, especially those related to environmental impact, maintainability and energy efficiency (Khanzode, 2012). The development of ICT and process improvement in the AEC can create conditions for productivity improvement that is so much appreciated by the companies, clients and public. The implementation of BIM and other intelligent technologies, effective procurement methods and collaboration practices is led by various industrial associations and public organisations, such as educational and research institutions, territorial administrations and public authorities.

2.2. Ontology of collaborative design

The design and engineering in most of the industries is a collaborative process that involves a number of individuals with expertise in different technical fields. The design phase of construction projects can be divided into several stages (Eastman et al., 2008: 151-152):

1. **Pre-design.** The construction projects typically start with the pre-design, on which the need for construction is assessed and initial building requirements are formulated. In infrastructure projects this phase involves customer, public stakeholders and consultants, and is typically merged with the second design stage.
2. **Conceptual design.** Initial, conceptual and schematic design are interchangeably used names of this design phase aimed at formation of design solutions, definition of shapes and spaces, materials and building systems. In infrastructure projects, **feasibility studies** are usually conducted

simultaneously with this stage to assess the economic feasibility of undertaking the project.

3. **General design.** On this stage (also called design development) the building plans, major building systems and materials are taken to a higher level of detail. The essence of the design solutions and the construction costs are defined on this stage.
4. **Construction-level design.** On this design stage, the final set of highly-detailed documents is generated for use in construction. It includes finished detailed plans of all building elements, specifications of systems and materials, plans of site work, and acceptance criteria for building systems. (Eastman et al., 2008: 151-152)

In order to understand the factors that determine the efficiency and effectiveness of collaborative design a closer view on the nature of design and collaboration is needed.

Design is a human activity that strives to improve the environment through creation of artefacts. This is done by formulating functions to be achieved and creating design that is made to perform these functions. Design is a purposeful activity that transforms the requirements (an envisioned function) into a design description of an artefact, and this description can be used to produce the artefact. Design description is the main outcome of design (Gero, 1990).

According to the Function-Behaviour-Structure (FBS) framework developed by Gero (1990), design process involves the following sub-processes:

- **Formulation.** Designer formulates how the structure must behave in order to perform the desired function.
- **Synthesis.** Designer generates the structure.
- **Evaluation.** Designer compares the actual behaviour of the structure with expected behaviour.
- **Reformulation.** If the actual behaviour is different from the expected behaviour, designer reformulates either the structure (type 1), or the expected behaviour (type 2), or the function (type 3).
- **Documentation.** Design description of the structure is created.

The design is performed in two contexts: the one within which designer operates and the one produced by developing design itself (Gero, 1990). The FBS framework is a notable framework that has been applied in design-related studies in different areas. The concept of **situatedness** developed in Gero's and Kannengeisser's (2004) following work on design ontology relates to a notion that designer's decisions to change the environment are affected by the current state of the environment (e.g. by existing design). "This means that the designers' concepts may change according to

what they are “seeing”, which itself is a function of what they have done” (Gero and Kannengeisser, 2004).

These concepts are important because they provide a generalised view on the design process as an iterative process in which change, reformulation and re-documenting are inherent. The design environment created by the designer affects how he sees the design later and what actions he takes next. In collaborative design, a designer is not only affected by his own actions, but also by those of other designers.

The development of design by a group of individuals requires shared vision of function and structure that is achieved through communication. The designers have to coordinate their individual inputs in design to be able to maintain this shared vision and to fit the elements of design together. The meaning of collaboration is that through the combination of specialised knowledge of designers the result is achieved that could not be achieved by any of the participants working alone. (Kvan, 2000)

The integration of knowledge is the goal of collaboration. Kleinsmann (2006, cited in Kleinsmann, 2008: 370-371) defines collaborative design (collaborative design) as the *“process in which actors from different disciplines share their knowledge about both the design process and the design content. They do that in order to create shared understanding on both aspects, to be able to integrate and explore their knowledge and to achieve the larger common objective: the new product to be designed.”*

The concept of **transactive memory**, developed by Wegner (1995), provides a process view on collaboration. Transactive memory occurs when an individual serves as an external storage of information for another individual. The individuals rely on common memory in order to retrieve information that each of them does not know, from other individuals. Transactive memory allows combining the memory of all the group members. (Wegner, 1995)

The notion of memory in the studies on information systems refers not specifically to past events, as intuitive understanding might suggest, but to information contained on a particular storage (Wegner, 1995), in the current case – an individual’s mind. Thus, the transactive memory includes information that existed before the design has started, including the professional knowledge and experience of individuals. The notion of memory in this case is equal to knowledge.

To retrieve information from the transactive memory, one must find its location; in other words, know who could provide such information. But each person does not know at every point of time what other people know. Each person is familiar with the knowledge-holding system from his own perspective, but the system is larger and more complex than that of any of the individuals (Wegner, 1995). Therefore, the knowledge

of the state of the knowledge-holding system is required at each time to ensure effective information exchange (Kleinsmann, 2008).

Collaborating designers develop **shared understanding** of the design, but also of the knowledge-holding system. “Shared understanding is a similarity in the individual perceptions of actors about either how the design content is conceptualized (content) or how the transactive memory system works (process)” (Kleinsmann, 2008).

The concepts of situatedness, transactive memory and shared understanding provide a basis for viewing collaborative design as a temporal process, in which the changes to the environment made by designers are affected by the sum of past actions that have formed the existing state of the environment.

In addition, the design is affected by the state of environment and the knowledge existing prior to the project. For example, a number of challenges in communication stem from differences among actors that exist initially before the design project starts. Those differences relate to initial knowledge and skills, vocabulary, professional values and goals (Kleinsmann, 2010; Pei, Campbell and Evans, 2009).

Following the point of view that communication is an autopoietic (self-organised, self-steered) system that is characterised by high level of uncertainty, Maier, Eckert and Clarkson (2005) argue that the possibility of any control over communication is limited. *“Influence, however, is possible if one manages to understand and connect to the internal logic of a system, i.e. the components and its connections and its specific rules by which it operates. The preferred solution seems to be to raise awareness and engage the designers in an ongoing learning process.”* (Maier, Eckert and Clarkson, 2005).

The notion of ‘internal system’ and its ‘logic’ in this statement shows similarity to the concepts of transactive memory and shared understanding discussed above. The concepts of transactive memory, shared understanding and communication as a social system suggest that the design is affected by designers’ knowledge about the team (knowledge-holding system) and teamwork process, and not only by the understanding of design object.

The framework presented on figure 5 illustrates the system of professional collaborative design based on the review of the literature on collaborative design presented in this section.

The framework depicts two specialised designers working together. The visible outcomes of their work include the design description and the information documented during the design that is not attributed to the design description (e.g. documented requirements, communication, solutions and other documented knowledge).

As illustrated in the framework, the design develops as a result of a cognitive process, in which the knowledge of many designers is combined. Here, memory incorporates all information possessed by designers at every point of time, and generally consists of the initial knowledge that occurred before the design started, and new knowledge. Designers develop both the knowledge of object being designed and the designing system (e.g. knowledge structure in the team). The combination of designers' memory forms the transactive memory. The framework is a proposal, meant to visualise the collaborative design system based on the reviewed articles. It has not been practically applied or tested in this study.

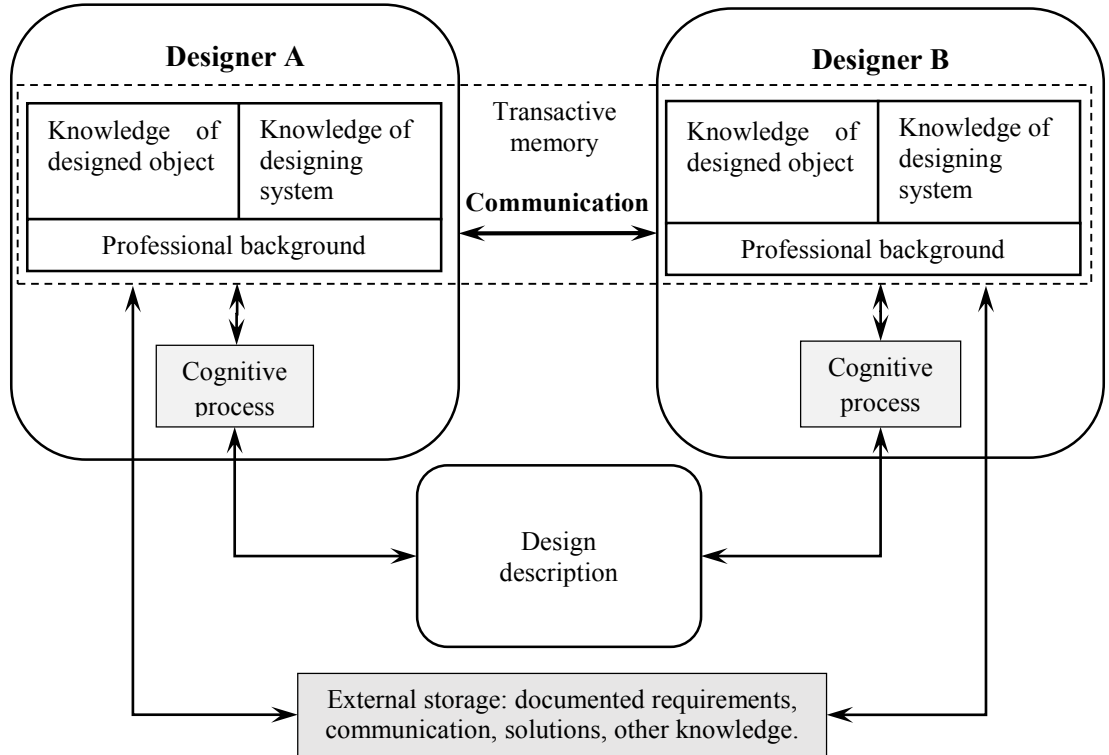


Figure 5: The conceptual framework of collaborative design system in professional domains

2.3. Application of Lean principles to collaborative design

‘Lean’ is a set of concepts, principles and methods aimed at increasing the efficiency and effectiveness in productive activities. It was developed in post-war Japanese automotive industry, which was rapidly developing and was later able to succeed on worldwide market competing with local counterparts, for instance, with US manufacturers on the US market.

The first and most fundamental ideas of lean manufacturing and philosophy were derived from the principles of Toyota production system (TPS) (Ohno, 1998). The lean approach focuses on delivering value to the customer and eliminating overburden (‘muri’), inconsistency (‘mura’), and waste (‘muda’) out of production system.

Waste is any activity that absorbs resources but does not contribute to value-creation: processing steps that are not needed, unnecessary stocks of materials, transportation, waiting for the upstream activity to be finished (Womack, 2003). Toyota production system outlines 7 basic types of waste (Ohno, 1998), which are typically found in manufacturing systems:

1. Waste of over-production (too much or too early production at cost of additional resources)
2. Waste of time on hand (waiting, inactivity of people and tools)
3. Waste of transportation (unnecessary movements of products and materials)
4. Waste of processing (more work or higher quality than required)
5. Waste of stock at hand (products and materials waiting to be processed)
6. Waste of movement (unnecessary movements and actions of people)
7. Waste of making defective products

The implementation of Lean starts from identifying what constitutes value in production system. In case of design, a creative activity with immaterial product, it is hard to define value and the sources of value, and to connect them to resources. Aapaoja (2014: 33-34), based on a number of studies, describes value as a relationship between benefits and sacrifices achieved through customer relationships. From the customer's perspective, value relates to quality – the degree to which his requirements are satisfied, and to which the design fits the purpose.

However, quality is not the only factor of design value. One can argue that more original and innovative solutions constitute more value than generic designs and require more resources and expertise to produce. Eastman et al. (2008: 154) describes the concept of information development, and suggests that different construction projects can be at different levels of information development, from standardised to highly innovative. The studies by Brown and Chandrasekaran (1985) and Brown (1996) identify three categories of design solutions in terms of creativeness, determined by the number of possible solutions and combination of variables in design: routine, innovative and creative design. Coyne et al. (1987) argue that the creativeness of design is defined by entropy (how much knowledge is available prior to design work), efficiency (time restrictions) and richness (number and variety of produced alternatives).

These concepts and the concepts found in the studies on collaborative design reviewed in section 2.4 view design largely as an information process. Indeed, the inputs and outputs of design are information (Kiviniemi, 2005: 26). Eppinger (2001) in his paper on management in product development projects mentions that the manager who wants to optimise the workflow in design-related projects needs to concentrate on the information flow and to understand the information needs of every task. For example,

when a product designer has to work with incomplete information from the previous task this may lead to rework (Eppinger, 2001).

It is logical to apply these statements to the AEC sector and to suggest that the opportunities for process development in design activities can be found in the domain of information management. This hypothesis is significant from the perspective of IT and BIM in particular.

Studies on information systems and information management contain parallels to the problems found in design process. For example, Hicks (2007) in his overview of lean approach to information management suggests that the notion of waste in information management relates to additional actions or inactivity that arise as a consequence of not providing appropriate and correct information to consumer when it is required.

A good example of such inactivity in construction sector is the process of sending a request for information (RFI) to another project stakeholder and waiting for the response (Eastman et al., 2008: 5-6). In collaborative design, the unavailability of information can be caused by the lack of input data, and can force designers to wait or work with incomplete (possibly wrong) information. Unavailability of information, therefore, can cause waste of time. The goals of information management are *“optimising the creation, representation, organisation, maintenance, visualisation, reuse, sharing, communication and disposal of information”*. (Hicks, 2007)

The studies on design stage of construction projects and concurrent engineering reviewed above suggest that design changes that occur because of mistakes or due to normal reformulation process, can cause re-work, which requires designers to spend additional time and undermines some of their previous work. While changes are inherent in a normal design process, their impact can be minimised if the need for change is recognised early enough in design process (see the next section). This is generally addressed by reducing the time between interrelated tasks and this way making the iterations shorter (Eppinger, 2001).

An important point that is not presented in the reviewed literature but needs to be mentioned, is that industrial approaches should be applied to design activity with caution. Design is a socio-cognitive activity, and not a controllable industrial process. Some activities in design that seemingly constitute waste (create no value) might be an important step in the cognitive process of design that will later result in development of design solutions. Even a seemingly wasteful activity, such as re-work, may result in a new understanding or idea that can contribute to the final outcome.

The search for waste in projects should be therefore focused on more tangible sources of waste, for example, unnecessary waiting. While the socio-cognitive element of collaborative design is self-regulating and hardly controllable, it is possible to control

the structural, mechanistic element including the way design information is handled, so that support is provided for the socio-cognitive process in terms of instruments and organisation.

2.4. The characteristics of collaborative design in project management

A number of conceptual problems result from the nature of collaborative design process. The early attempts to describe the design process have viewed designing as a sequential activity, in which the design evolved in a series of steps from early conceptualisation to testing and release. The actual design projects at that time were planned according to this principle.

In the software industry, however, this manufacturing-like method of design proved to have significant flaws. In the middle of the last century, the early industry was characterised by high rate of delayed or failed projects (Larman, 2004: 101). It was typical that the project teams created hundreds of pages of paper-based documentation in order to manage information, but such detailed documents were incomprehensible (Larman, 2004: 63-108).

The Waterfall model, first formulated by Royce (1970) in his well-known paper on development of large software systems, was presented in an article that criticised the linear software development. The model became a classic illustration of a linear design process applicable in other domains of design. The process is presented as a sequence of steps, from formulating the requirements to testing and deployment, where each step is performed upon completion of the previous one (figure 6).

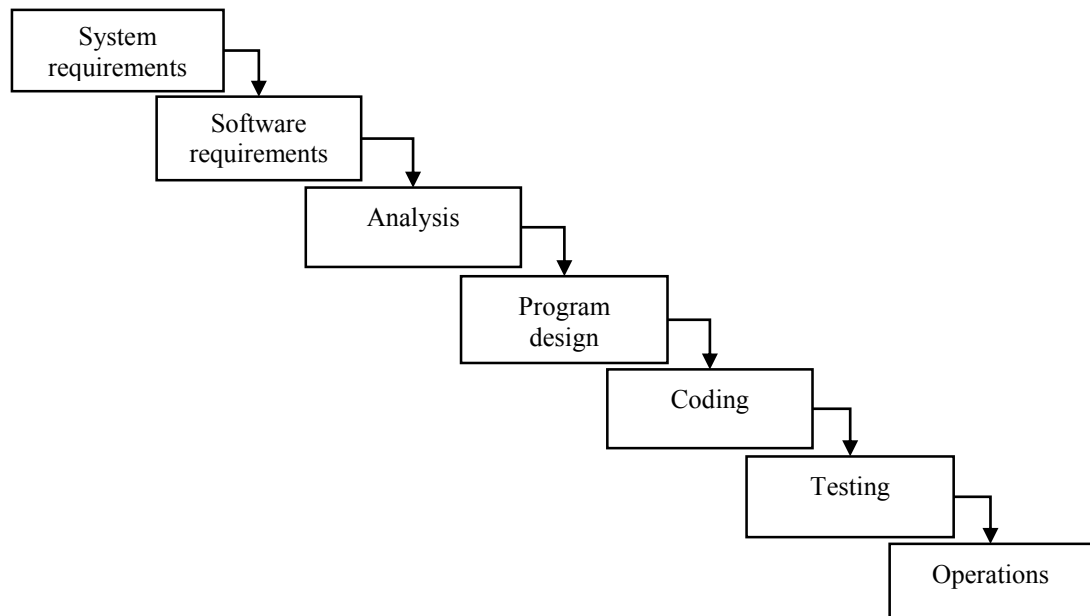


Figure 6: Implementation steps to develop a computer program for delivery to a customer (Royce, 1970)

The problem in this model is that a possible change in requirements or an error on earlier stage of the process undermines at least partially the progress that has been made earlier, and requires returning several steps back in the process. Management of changes is a conceptual problem of collaborative design that is directly related to dependency of tasks. As suggested by the design theory discussed in section 2.2, change is inherent in design. When the tasks are done in a sequence, changes to design decisions made on early stages undermine related tasks that have been carried out later. Design changes, therefore, imply the cost of re-designing.

Royce (1970) describes the impact that major changes in design have on software development: *“The required design changes are likely to be so disruptive that the software requirements upon which the design is based and which provides the rationale for everything are violated. Either the requirements must be modified, or a substantial change in the design is required.”* The second statement is similar to the concept of reformulation suggested by Gero (1990).

On the project level, the cost of change for design project increases as the design proceeds to completion, according to the study on construction projects cited by Eastman et al. (2008), figure 7.

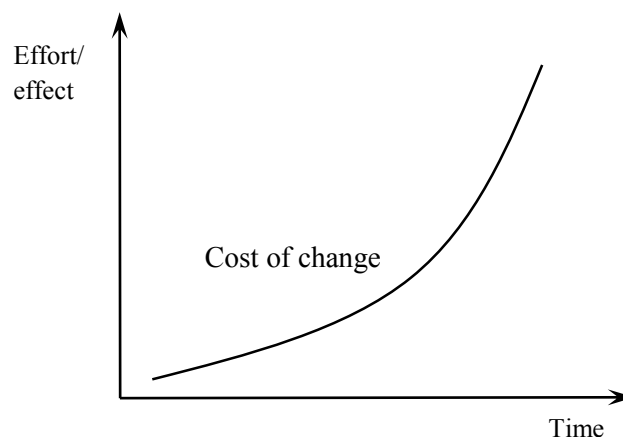


Figure 7: Cost of changes for design services (adopted from CURT, 2007, cited in Eastman et al., 2008: 153)

Eppinger (2001) in his paper on product development projects mentions that there are different types of dependency between project tasks. Some tasks can be put in sequence, when a subsequent task utilises information from the previous task. Such dependency produces *feedforward* information exchange. However, in creative activities there are also tasks that are mutually dependant and require *feedback* loops, when information from the later task causes change in a previous one, and causes reiteration and rework. Such change loops are a distinguishing characteristic of creative, innovative activities. (Eppinger, 2001)

However, Eppinger (2001) states that many of the iterations that typically occur in product development projects are marginally beneficial or wasteful, adding to project costs due to rework they cause, and hence iterations must be managed. Typically it involves shortening the iterations, since *“keeping interdependent tasks separate can cause considerable waste”* (Eppinger, 2001). Royce’s example (1970), in which a change on a later phase of a project undermines the whole project, is an extreme example from Waterfall development where the length of one design iteration is equal to the length of the project.

Software industry has eventually shifted largely from the Waterfall paradigm to Agile methodology (Larman, 2004; Beck et al., 2001). In the foundation of this new approach was the understanding of iterative nature of design and of the importance of teamwork and collaboration. From the process perspective, most of the agile methods, such as Scrum, aim at fixing design iterations to short time intervals and building products incrementally, in steps during which the developers work in parallel on one particular module or function of the product. On completion of each increment, developers test the product and plan what should be done next, usually prioritising the functions that have more importance or value for the customer. For example, the Scrum method (Schwaber & Sutherland, 2013) involves short iterations called ‘sprints’, typically a few weeks long. Team meetings are held after each sprint, on which the developers report on their progress and discuss the direction of their future efforts.

The conceptual problems of collaborative design are also observed and described in design-related literature from ‘heavy’ industrial domains, including manufacturing and shipbuilding. The changes in design paradigm led by industry best practice and enforced by scientific research on design have meant that the manufacturing-based linear view on design process was largely discarded in the research. Similarly to a study by Eppinger (2001) mentioned above, Parsons, Singer and Sauter (1999) in their study on concurrent marine design highlight *the iterative nature of design activity* and the coupling of design tasks:

- *“Planning. Design tasks cannot be sequenced in detail. There is generally no way to progress through the design analysis and decision-making in an organized way such that all the information is available when necessary to each designer. Thus, the design spirals.*
- *Coupling. Designers think locally, but they are tightly coupled with other designers. Decisions that one designer makes affect the decisions that other designers have made. This constant need for re-evaluation as a result of changes in the design interfaces can lead to lengthy cycles of iteration and change.*

- *Prioritizing. Designers have no common language for comparing the importance of issues.*”

The concept of Concurrent Engineering (CE) was created in research on automotive industry product development, and is a part of lean approach to product development. Lean product development focuses on maximising the value and reducing the delivery time through supplier involvement, integrated cross-functional teams, concurrent (parallel) engineering and strategically-oriented management (Karlsson and Åhlström, 1996).

Concurrent Engineering (CE) is a type of design process where activities of different disciplines are planned to be carried out in parallel. The purpose of CE is:

- to reduce the delivery time (Bogus, Molenaar and Diekmann, 2005; Krishnan, Eppinger and Whitney, 1995), and
- to improve quality by increased collaboration and early involvement of stakeholders who are specialised in production activities (e.g. subcontractors) in design (Licker et al., 1996; de la Garza et al., 1994).

Overlapping the tasks can be a problem, if the dependencies between tasks are not known. When the downstream activity has to start without the necessary information from the upstream activity it has to be based on preliminary information and assumptions that may change when the upstream activity is completed. The resulting delay can eliminate the advantage of overlapping the tasks. This problem is called the iterative overlapping problem. (Krishnan, Eppinger and Whitney, 1995; Eppinger, 2001; Bogus, Molenaar and Diekmann, 2005)

Therefore, the team must understand the effect of the design changes on downstream activities (Krishnan, Eppinger, and Whitney, 1995; Bogus, Molenaar and Diekmann, 2005; Eppinger, 2001). The Design Structure Matrix (DSM) tool aims at reducing the waste in product design projects and relies on identification of dependencies between tasks based on assessment of the information needs of each task, in order to plan the iterations and regroup tasks (Eppinger, 2001). When describing the application of DSM, Eppinger (2001) mentions: *“When we draw a DSM for a product development process, we go to the grass roots and ask individual development teams what they need from other teams to do their jobs.”*

The Last Planner system of production control (Ballard, 2000) is based on a similar approach. This planning and control system finds its application in AEC projects. The system involves direct participation of project members in planning activities. First, the project members work on understanding the interrelation of tasks and the information needs of each task. Then they provide their estimates of how long it takes

them to finish the tasks. This results in a detailed schedule, which is reviewed throughout the project.

Set-based design is an extension of concurrent engineering practice that addresses the optimisation problem of design. The optimisation problem stems from the fact that the design is limited by a number of constraints, such as budget and building space. This problem relates to the interdependency of tasks. The constraints imposed on the interrelated tasks mean that the customer value added by each of these tasks is reversely proportional to the value of the other elements. Maximising value outcome for one of them would decrease the value of others. An example of such relationship is the limit of space in a car dashboard: air condition system, audio system, navigator and controls conflict with each other in terms of space. The question is how the design should be optimised so that it delivers the maximum overall value to the customer with the given constraints.

In conventional point-based design the structure of critical and high-level elements is determined and fixed at an early stage, and less critical or low-level systems are selected to fit the high-level design. However, the elements that are given higher priority in a project would not necessarily result in the highest value for the customer. Prioritising individual tasks within a project leads to sub-optimisation of overall value.

In set-based CE (figure 8), first implemented in Toyota, the design process is organised as a parallelised process of narrowing down the scope of alternatives for every system, function or element in design, so that the optimal trade-off between them is achieved (Licker et al., 1996; Parrish et al., 2007).

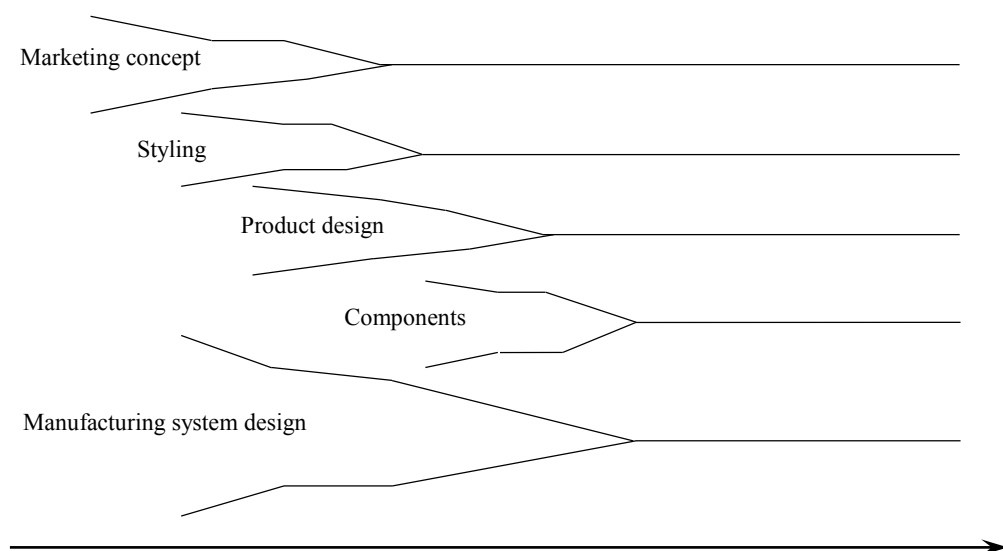


Figure 8: Parallel set narrowing process sketched by a Toyota manager (Parsons, Singer and Sauter, 1999)

Application of concurrent engineering and set-based design to AEC industry has been discussed broadly in the literature (Parrish et al., 2007; Anumba and Kamara, 2012; de la Garza et al., 1994). However, for set-based design there was no empirical evidence of application in the AEC in the literature, although there are no apparent barriers to such. The general principles of CE, such as the emphasis on communication and involvement of production site and sub-contractors in design, are relevant to the AEC industry and can be recognised in the integrated approaches to AEC project delivery.

In addition to problems of collaborative design mentioned above, there are difficulties for knowledge acquisition and dissemination in project-based collaborative activities. Knowledge transfer and learning are generally difficult in project-based organisations (Gann & Salter, 1998). In such firms, the design and production have temporary organisation and result in one-off or highly customised products. Project process usually causes discontinuities in the knowledge flows and learning. There is typically a lack of connection between different business units of a project-based firm, and project-based learning is isolated from company-wide business process. The lack of organisational coherence in project-based firms hampers the accumulation of knowledge. (Gann & Salter, 1998)

The problem with knowledge management is magnified when knowledge exchange between different organisations is concerned. Traditional AEC practice, characterised by 'over-the-wall' process, paper-based documentation, individual goals and restricted information flow, does not support knowledge exchange and conversion (De la Garza et al., 1994). Various design and production disciplines form knowledge silos. Therefore, the emphasis on stakeholder integration and communication in the design-related literature is also rationalised by facilitating knowledge transfer and learning. The problems of knowledge conversion and exchange in AEC have a potential to slow down the adoption of new technology, such as BIM.

To summarise, the methods of product development applied in different industries to deal with conceptual problems of collaborative design include:

- Project integration and early involvement of project stakeholders in collaboration;
- Meetings, face-to-face communication and shared workspaces;
- Balanced iteration frequency and parallelism of tasks aimed at increasing collaboration and mitigating the impact of design changes;
- Involvement of teams in project planning and identifying dependencies between tasks;
- Set-based approach to optimisation of design value;
- Systematic management of communication, requirements and knowledge.

The summary of directions for process improvement in collaborative design and the list of corresponding literature sources are included in table 1.

Table 1: The possible directions for process improvement in design projects, based on the reviewed literature

Direction	State		References
	Undesirable	Desirable	
Concurrent process	Sequential workflow, 'waterfall' process	Concurrent workflow; Managed iterations; Understanding task dependencies	Royce, (1970), Parsons, Singer and Sauter, (1999), Parrish et al., (2007); Anumba and Kamara, (2012); de la Garza et al., (1994); Bogus, Molenaar and Diekmann, (2005); Krishnan, Eppinger and Whitney, (1995), Licker et al., (1996), Eppinger (2001)
Value optimisation	Point-based design	Set-based design	Licker et al., (1996); de la Garza et al., (1994)
Stakeholder integration	No integration; 'over-the-wall' process	Early stakeholder involvement; Integrated delivery; Trust and collaboration	Licker et al., 1996; de la Garza et al., 1994, Aapaoja, 2014
Co-location	Personal workspace, few meetings	Shared work space or frequent meetings	Khanzode, 2013; Eppinger (2001); Kvan (2000)
Knowledge management	Knowledge silos, learning disrupts after projects	Project-wide and company-wide knowledge sharing	De la Garza et al., (1994); Gann & Salter, (1998)

2.5. Benefits of technology for collaborative design in construction sector

The possible synergy between the information technology and the design process improvement is not studied enough. However, the review of the literature regarding BIM and other IT suggests that the information technology innovation has already made and will continue to make a large impact on design.

The studies by Kleinsmann (2008; 2010) identify the variety of factors that affect the development of shared understanding between project actors. The author categorises them between three levels. The large share of the factors for achievement of shared understanding relate to information, knowledge and communication.

For example, the second most frequent factor on the *actor* level identified in the study was the ability to make transformation of knowledge when exchanging it between disciplines. At the *project* level, the most frequent factor was the efficiency of information processing. The examples of barriers related to it provided in the study include late information delivery to the receiver, such that he cannot move on with the next task, or that the receiver does not know the status of a document. The second most occurring factor at this level was the quality of project documentation. (Kleinsmann, 2010)

Better information management in projects can reduce waste. The analysis of New Civil Engineer (1991, cited by Baldwin, Thorpe and Carter, 1996) estimated that around 25% of cost in construction projects carried out at that time could be eliminated if construction information was managed effectively.

BIM, as an approach to management of building information in projects, is viewed as a potentially disruptive innovation that can lead to major improvements. The impact of BIM relates to the information process that underlies the physical construction activity. The understanding of design as an information process and the overview of conventional problems faced in design suggest that BIM can contribute to higher efficiency and better quality of design. The benefits of BIM that can impact the design stage of projects and are already utilised today include:

- **Visualisation.** BIM gives even more advantages in relation to this general benefit of computer-aided design: more efficient 3D design compared to CAD and the integration of discipline-specific models can help evaluating design options and solutions better (Eastman et al., 2008: 18). Visual channel is a primary communication channel in design, because it can effectively represent complex engineering objects and relationships that cannot be reduced to unambiguous verbal descriptions (Maier, Eckert and Clarkson, 2005).
- **BIM as a design collaboration platform.** The model shared by designers can facilitate collaboration between different technical areas. It is possible to exchange designs directly in the model, shifting away from traditional 2D-based approach to data exchange. Using BIM as a multidisciplinary collaboration platform can be possible with the help of Industry Foundation Classes (IFC) and model server technology. (Plume and Mitchell, 2007; Eastman et al., 2008: 19; Poerschke et al., 2010; Singh, Gu and Wang, 2011)

- **Clash and error detection.** This benefit results from the possibility to integrate discipline-specific design data. Savings from clash detection are realised during construction phase of the projects. (Eastman et al., 2008: 19).
- **Cost estimation, quantity take-off and engineering analysis** tools that use data integrated in BIM, can support design development. Both cost estimations and functional assessments can be faster and more precise with BIM, allowing better evaluation of design alternatives starting from the earliest design phase and enabling value optimisation in the project as a whole. Design analysis tools can be used to improve energy efficiency and sustainability of buildings. (Eastman et al., 2008: 18; Sattineni and Bradford, 2011)

As it was already mentioned, in spite of the possible benefits the technology still suffers from software interoperability problems: different technical disciplines and lifecycle phases require specific software solutions, and data transfer between software is sometimes limited and can require substantial manual intervention. As Eastman et al (2008: 15) explain, the companies can either use a set of interoperable software tools from the same vendor, or procure software from different vendors that can exchange data using industry standards. The problem of software interoperability is addressed by such standards as Industry Foundation Classes (IFC), Land XML and GIS – the common formats of data exchange developed by industry community or organisations such as BuildingSMART for IFC, or National Geospatial-Intelligence Agency for GIS.

A relatively old study on electronic information exchange and alliance contracting by Baldwin, Thorpe and Carter (1996) explores the issues of information management. Although the set of technologies discussed in this paper is largely outdated (e.g. email), the paper contains principles interesting in today's context. The concept of electronic exchange of 3D CAD data described in the article is relatively close to BIM. The following benefits of electronic information exchange are identified (Baldwin, Thorpe and Carter, 1996):

- Guaranteed delivery of data
- Improved quality of data
- Reduced data handling
- Improved communication between the alliance partners / stakeholders, and
- Reduced risk of project delay.

The examples of interoperability problems, the delay of sending RFIs, the 'over-the-wall' process and other inefficiencies discussed earlier show that, even 18 years after Baldwin's, Thrope's and Carter's study, there is still much room for improvement concerning all the benefits suggested by them.

Despite the benefits of IT, physical communication between people is still essential. The importance of face-to-face communication in collaborative design is highlighted

by the majority of reviewed studies and gives justification for such collaboration methods as Scrum meetings (Schwaber & Sutherland, 2013) and co-location in Big Room (Khanzode, 2012). According to Khanzode (2012), co-located teams are able to design systems that better complement and support each other's functions, and spent less time on looking for up-to-date information or working with outdated information. The potential role of technology is to aid co-working, for example, by providing visual representations of the design during work meetings. Kiviniemi (2005) explores such capabilities of visual technology in his study on decision-making during design phase of construction projects.

Eppinger (2001) states that the exchange of information is a 'lifeblood' of design, innovation activities. He adds: "*When an electronics company's circuit designers know what the casing designers are doing, they design a better fitting circuit for the casing. And when the casing designers know what the circuit designers need, they design a casing where it's easier to put in a better circuit.*" This simple example, equally relevant to other areas of collaborative design, can be used to outline the potential role of BIM, and other IT, in maximising the value generated on design stage of AEC projects.

2.6. Conclusions and introduction to empirical study

The review of the literature suggests that the benefits of BIM in the design phase of construction projects have been studied considerably less than such in the construction phase. The lack of literature directly addressing the topics related to design in the AEC domain was one of the reasons why the literature review included studies from different industries, such as software and manufacturing. This approach allowed understanding different perspectives to the process improvement in collaborative design. The similarity of principles that determine the efficiency and quality of design according to studies from different domains shaped a theoretical background for this research.

The key goal of this study is to identify the currently achieved and the potential benefits of BIM for design projects in infrastructure sector. This search for benefits is to be conducted via close examination of the current design process in several companies, and by questioning the project teams about their perception of BIM and the design process. This examination is expected to result not only in a review of benefits of BIM, according to the research question 2, but also in the comparison of the current state of design process to its potential state, and the recommendations of what improvement steps can be taken by companies, regarding the technology or otherwise. These two practical objectives are covered by the research questions 3 and 4.

RQ2. What is the potential role of BIM and other technologies in maximising the efficiency and effectiveness of collaborative design in construction projects?

RQ3. What is the current state of design practice and BIM implementation in the infrastructure sector in Finland? How do the professionals perceive it?

RQ4. What actions can be taken by the design companies in infrastructure sector regarding the technological and process development in order to increase performance in design activities?

The impact of BIM is to be studied on different aspects of designing. The identified elements of process improvement that will guide this research include:

- Concurrent process, project workflow and iterations, project planning
- Optimisation of value delivered in the project
- Stakeholder integration, contract-wise and information-wise
- Co-location, meetings and other teamwork practices
- Communication media
- Knowledge management
- Data exchange, information management

Some studies connect the implementation of BIM and other IT with the stakeholder integration and relational methods of contracting (integrated project delivery). The notion that stakeholder and cross-discipline integration is beneficial for the projects was found in both the literature on AEC and on Concurrent Engineering in manufacturing domain. Due to dominance of public contracts in infrastructure development in Finland and the consequent legal barriers for using relational contracting in infrastructure projects, it will be especially interesting to find out how the possible directions of process improvement revealed in the literature study can be applied to projects that use traditional procurement methods.

3. Methodology

3.1. Case studies

This research utilises case study methodology. The data for the empirical study was collected in four design projects in infrastructure sector in Finland carried out by two companies: two finished road projects (projects A and B) in Company Alpha, one finished railway project (project X) in Company Beta and one unfinished railway project (Project Y) in Company Beta. Projects B and X were conventional, and projects A and Y used BIM: the contracts included creation of collaboration models and delivery of models to the owner (table 2).

The finished projects were carried out several years prior to the study; therefore, a substantial recall bias could occur if designers were asked about their perception of past projects. Because of that, it was decided to obtain as much verifiable, documented

data for the past projects as possible (e.g. meeting notes, schedules, reports), and to collect perceptions as to the date of the research without binding them to the case projects. This way the focus of the study included not only the case projects but also the case teams and companies on a longer term.

Table 2: Case projects

Company	Case project	Case team	Project field	BIM	Year when finished	Number of participants	
						1 st workshop	2 nd workshop
Alpha	A	1	Road	Yes	2013	4	4
	B	2	Road		2010	4	4
Beta	X	3	Railway		2013	7	5
	Y		Railway	Yes	Ongoing		

The division explains why a number of different methods were used in the research, such as cross-functional project diagrams and questionnaire survey, and the subsequent division in research data between case data and general data and perceptions. A benefit from utilising different methods was that methodological triangulation was achieved to enhance the credibility of results.

Prior to the study, semi-structured interviews were conducted with the managers of each case project to obtain the initial information about the projects. The interviews were audiotaped and transcribed.

The main part of the empirical study was to conduct workshops with project teams. Two workshops were held for each project, at which project managers, BIM coordinators and 2-3 key persons from different technical areas were able to discuss the projects.

Because projects X and Y were performed by the same project management team, most of the attendees were the same for the corresponding workshops. In addition, these four workshops included an independent BIM expert from company Beta.

All workshops were conducted in a semi-structured manner, with some questions being prepared in advance and some questions emerging in the discussion. The main language was English, but Finnish was also used. Maila Suvanto from Vianova Systems Finland Oy, who was an instructor of this thesis research, assisted with the workshops and helped to translate the discussions. The workshops were videotaped, the duration of each workshop was 3.5 hours.

A first and a second workshop were planned differently, and served different purpose: the first one – to obtain general data, and the second – to conduct a detailed discussion.

On the first series of workshops the project teams provided general details about the projects, described the project events and problems. They used post-it notes to create maps of the projects that reflected the main project events, tasks and data exchange. The secondary data was also collected:

- Logs of received and created data; logs of design revisions
- Project schedules, milestones
- Meeting dates and agendas, meeting notes
- Project diaries
- Reports, “lessons learned” notes

To create the project maps, the teams were given coloured sticky notes and asked to write down the various project activities and corresponding dates, using their laptops to gather information right away. They were also asked to write their names or initials on the notes. There were five colours in total, and each related to a particular type of process step or event: ‘Task’, ‘Received item’, ‘Delivered item’, ‘Meeting’, and ‘Event’ (see examples on figure 9). The filled notes were then put on a canvas in a chronological order.

Date
<ul style="list-style-type: none"> – What did you deliver? <ul style="list-style-type: none"> - data - design, drawing - task - decision - etc. – To whom was it meant? (who received/used it?)

Date
<ul style="list-style-type: none"> – Meeting participants – Agenda, reason – Results, decisions

Figure 9: Examples of note templates: ‘Delivered item’ (left) and ‘Meeting’ (right)

The project maps, workshop recordings and secondary data were analysed before the second series of workshops. The data was used to create detailed swimlane (cross-functional) process diagrams (Damielo, 2011: 6) of the projects, and to formulate the agenda for the following meetings. The swimlane diagrams were presented to the teams on the second workshops. The teams discussed the events and problems discovered in the data and corrected a few inconsistencies in the diagrams. The discussion was planned to test the hypotheses and cross-check the questionnaire data. The broad discussion of different BIM-related and process-related topics allowed drawing a picture of professionals’ perceptions of these topics.

The participants were asked to name the problems that are most important for their work. Each team was asked to select 2-4 biggest problems, and every participant was asked to take part in the selection and had his opinion heard. The named problems

were largely repeating the problems outlined in the questionnaire study that was held in the beginning of first workshops. After selecting the top problems, the teams were asked to split in pairs and discuss the reasons that were likely to cause these problems, using the cause-and-effect ‘fishbone’ diagram, also called Ishikawa diagram by the surname of its author (1950) (figure 10).

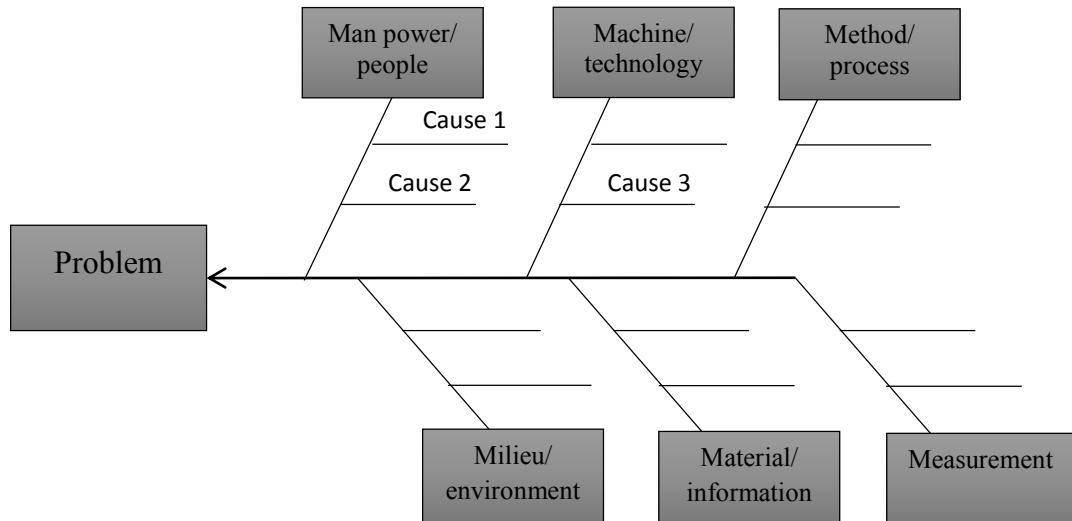


Figure 10: Fishbone (Ishikawa) diagram

In fact, many of the suggested ‘causes’ could be attributed to more than one category at the same time, according to the designers (e.g. Method, and Process and Milieu, and Environment). This was not a problem, since the purpose of the diagram was to serve as an aid tool for discovering the problems and causal relationships rather than a tool for categorising problems. At the end of the workshops, the professionals were asked to write down the criteria of the hypothetical ‘ideal project’ as they see them, assuming that unlimited resources were available.

3.2. Sentiment analysis

The method of sentiment analysis (Wilson, Wiebe & Hoffmann, 2008) was adopted in the research to analyse the workshop recordings. The main purpose of using this method was to support the credibility of results provided by qualitative methods, by applying quantitative methodology to the textual data from the workshops.

The video recordings from the workshops were put on paper as narrations with time markings. The narrations reflected each statement made during discussions by the project team members, but were not verbatim. The researchers’ statements were excluded. These narrations were analysed with spreadsheet tools. The results of this analysis are presented in Chapter 4.

For enabling the analysis of textual data, the data was transformed into spreadsheet format: each recorded sentence or phrase with a complete meaning was transformed into a short readable statement that reflected the original meaning non-redundantly, but could be handled as a separate entity for quantitative analysis. The amount of collected data allowed performing such transformation and analysis with spreadsheet tools.

The analysis included two steps: the categorisation of statements and assigning the sentiment index to the statements. The categories, or topics, were derived from analysis of textual data and included:

- Changes, requirements
- Designing
- People
- Modelling/data
- BIM implementation
- Tools
- Cost estimates
- Clash detection

The categories were not exclusive. If a statement related to several categories – as many categories as needed were assigned to this statement. Adding a new category for the matter of analysis was easy – any category could be assigned to a statement if the statement related to it, so the statement did not have to be excluded from the previous category to be assigned to a new one. However, the categories were formulated in such a way that most of the statements could be attributed to only single categories, and so that the number of categories stayed reasonable. In this sense, the categories were suggested by the data.

The approach was more flexible compared to if pre-defined categories derived from theory were used, because the analysis was not restricted by older assumptions and frameworks that had limited relation to the research data. Particularly, there was no need for attempting to attribute any statements to categories that they did not strictly belong to only because they went beyond the scope of theoretical frameworks.

In addition to being assigned with categories, each statement was marked with a sentiment index: negative, positive or neutral (see table 3). A sentiment was given a neutral index in most cases, and an index other than neutral was only assigned when the attitude was explicit from the text (for example, if the word “problem” was mentioned).

Table 3: Analysing the workshop recordings (fragment)

Item no.	Original statement	Short statement	Sentiment (1 – neg., 2 – pos.)
67	09:08 Traffic signs budget somehow started to grow, and the PM noticed that, and it turned out that the traffic sign was taken to too detailed level, almost construction design level.	Traffic signs design was taken to too detailed level. The problem was noticed because the cost started to grow. (PM didn't see the designs?)	1
68	11-12 Construction costs were calculated both at the initial design stage and in road design, the number wasn't much different, it was 50 M EUR.		2
69	13:20 Construction risks and construction cost estimate during design didn't have to be considered that much on this stage, because all major decisions were made during general planning. So the estimates didn't change that much.	All alternative options were considered during previous design stage, therefore construction cost estimate did not play a big role.	
70	But generally, one big benefit that BIM can give is more accurate cost estimation while doing the design.	One big benefit that BIM can give is accurate cost estimation during design.	2

The limitation of such manual approach was that, compared to more complex methods that employ mathematical algorithms, this approach to some degree was based on interpretation. However, the work was carried out in such a way as to minimise the impact of interpretation. As Chapter 4 shows, there is substantial amplitude of variation between the results for different cases; in addition, the results of this analysis are consistent with results suggested by other methods and lead to coherent explanations.

Only semi-structured workshop discussions were included in the analysis. Discussions of cause-and-effect diagrams and principles of ideal projects were not included because they did not explicitly relate to the case projects, and because the double inclusion of the same data in different analyses would undermine the results.

In the analysed discussion itself many statements did not relate to the cases alone; however, excluding these statements would not be possible because the division between case-related and general statements was not clear. Deciding upon such division would add a large element of researcher's assertion to the analysis. In addition, there was a possibility of recall bias when designers discussed projects that had happened several years ago.

Therefore, it must be noted that the workshop discussions and the results of sentiment analysis are likely to represent the cases at least to some extent through the prism of current state of work practice within the case companies at the time of the research. However, the effect of recent experience on results is arguably low, because most of the provided statements relate to cases and because the results of the sentiment analysis are compatible with the unique characteristics of the case projects, which are also reflected in other data.

3.3. Questionnaire

In the beginning of the first workshops, a paper questionnaire was given to the attendees in order to obtain the individual perceptions and opinions. This allowed collecting responses that were not affected by the authority of project managers or project teams as a whole, or by a bias that could be introduced by researchers through verbal discussion.

Open-ended questions were placed in the first part of the questionnaire to challenge the initial research assumptions and minimise the influence of researchers. The respondents were asked to state three problems that they deem most important in their work practice, and list three most important benefits of BIM according to their knowledge. This approach allowed discovering more issues than acknowledged by the researchers when preparing the questionnaire.

These questions were followed by attitudinal questions, in which the respondents were asked to rate their satisfaction in different aspects of work practice in their company. The respondents were also asked to rate different aspects of BIM suggested by the questionnaire. Bipolar rating scales of 7 points were used to ensure sufficient distribution of answers. In addition, the respondents were asked to provide non-attitudinal information on their work experience, education and BIM experience, and to rate their knowledge of BIM.

The latter allowed evaluating the strength of the responses to BIM-related questions. Two explicit ‘validation’ questions on knowledge of BIM were asked in different places in the questionnaire: “How much do you know about BIM?” and “How well do you know about the features of BIM, in general?” In addition, the respondents were asked to provide the number of BIM projects in which they had participated. Cross-checking between responses showed that this evaluation was valuable: the respondents who reported no experience of working in BIM projects also reported less or no confidence in their knowledge of BIM, and, most importantly, there were major differences in responses to most of the questions between the groups with different levels of BIM experience.

The low number of respondents (15 in total – all workshop attendees filled in the questionnaire) would not normally allow generalising the questionnaire results outside the case projects. However, the questionnaire data complemented and validated other case data, and there were no contradictions between results provided by different methods. The number of respondents is suitable for case study methodology chosen in this research. Figure 11 represents the research data framework and specifies the sources and types of collected data.

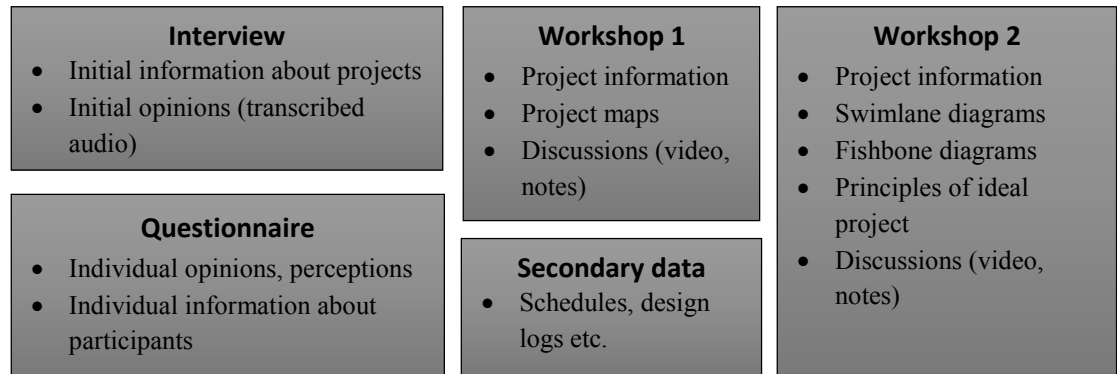


Figure 11: Data collected in the empirical study

4. Results of the empirical study

4.1. Questionnaire study

The questionnaire (appendix 1) distributed to the attendees in the beginning of each of the first workshops included the questions about the attendees' BIM experience, their understanding of BIM functions and the perception of design process. All workshop attendees have filled in the questionnaires. The respondents with no knowledge of BIM whatsoever could skip the BIM-related questions. The designers were also asked about their education and experience. Four designers had a Bachelor's degree, and eleven had a Master's degree. The experience in the field was distributed as shown in table 4.

Table 4: Experience of workshops participants, reported in questionnaire.

	Years of experience in the current field				
Option (years)	b. 1-3	c. 3-5	d. 5-10	e. 10-20	f. >20
Respondents	2	2	5	1	5

There were differences in team member experience between projects. The participants from Team 1 (project A) had 5-10 years of experience with the exception of one participant with 1-3 years of experience, in that sense it was the 'youngest' set of respondents. It was also a BIM project team. Team 2 (Project B) had 1 participant with

more than 10 years of experience and 3 participants with more than 20 years, which is the highest experience among the cases. It was involved in a non-BIM project. Team 3 included two professionals with 3-5 and 5-10 years of experience, and one respondent in each other category, being the most diverse project team in terms of experience.

With regard to BIM experience, the designers could be divided in three groups, with very straightforward borders between groups:

- Group 1: five respondents with no experience in BIM
- Group 2: four respondents who had 1-2 BIM projects – ‘novel users’
- Group 3: six respondents who have reported participation in more than 7 BIM projects – ‘BIM experts’.

The questions on BIM knowledge and experience were meant to evaluate the strength and validity of responses to other BIM-related questions. The divisions between groups with different BIM experience were significant. The participants’ level of satisfaction with BIM (figure 12) and their willingness to work in BIM projects in future (figure 13) depended on BIM experience and were highest for BIM experts.

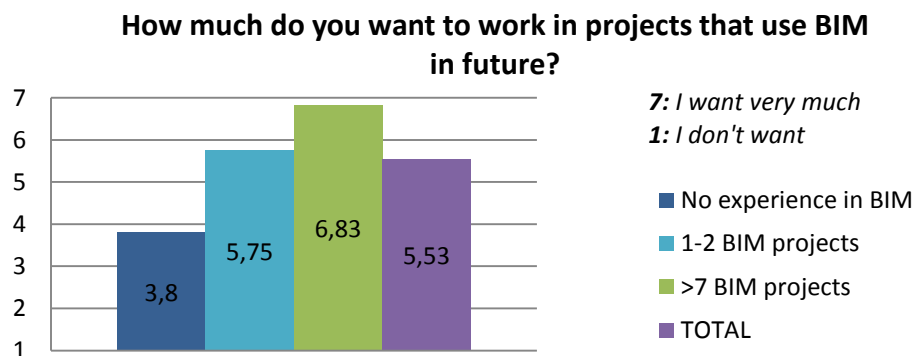


Figure 12: The willingness to work in projects that use BIM, in relation to BIM experience (note: the strength / credibility of answers may differ between groups).

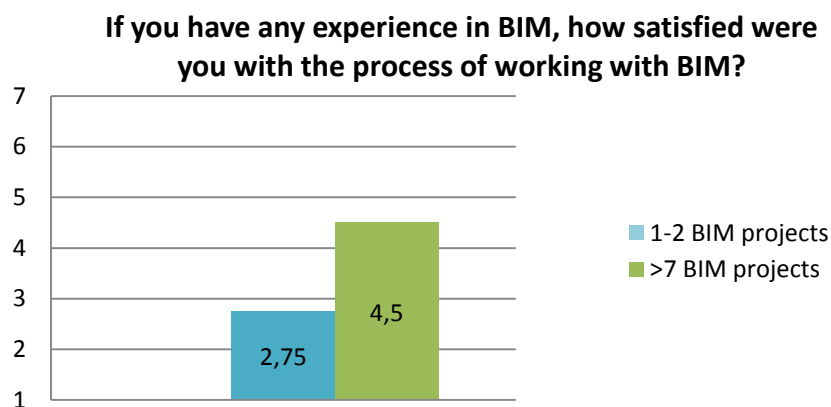


Figure 13: The level of satisfaction with the process of working with BIM in relation to BIM experience.

BIM experts were more positive in their assessment of the effects of BIM on their work. Figure 14 shows the responses to the matrix of scale questions, in which the designers were asked to rate different aspects of BIM from very negative (-3) to very positive (+3); the possibility to give “I don’t know” answer or no answer at all was provided too.

According to your understanding of BIM, rate the effect that BIM has on the following parameters (mean numbers):

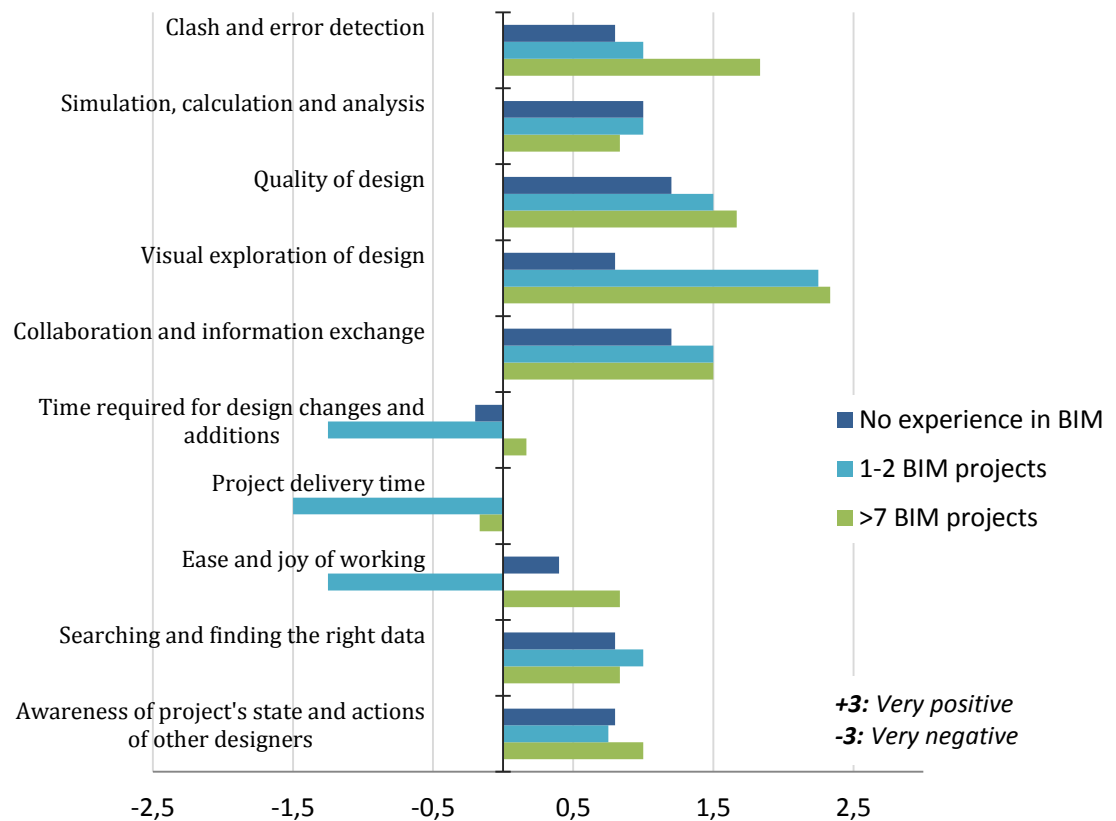


Figure 14: The perception of the effect of BIM on different aspects of designing, in relation to BIM experience (mean numbers).

The figure shows that novel users were more concerned about the difficulties of using new technology. The impacts of BIM on (1.) time for design changes and additions, (2.) project delivery time and (3.) ease and joy of working were rated the lowest by novel BIM users, and BIM experts were neutral when stating their attitudes about the effect of BIM on time (1. and 2.), acknowledging benefits with regard to ease and joy of working (3.). Moreover, the analysis of questionnaire showed that Case A team has viewed the impact of BIM on these three parameters most negatively compared to other teams (for Team 1 mean numbers were -0.75, 0 and 0 for the three parameters respectively, while the overall mean numbers for attendees were 0, 0.92 and 1).

The BIM experts, when describing the general reasoning of designers who resist to the new technology, mentioned that many designers see BIM as ‘extra work’ (mentioned

on project A and Y workshops). The data presented in section 4.2.1 shows that the concerns about attitudes and skills of individual designers were especially strong among the respondents from Case A, in which designing and BIM were carried out as separate processes by separate project management teams.

An interesting finding from Figure 14 is that the respondents with no experience in BIM showed the similar general pattern of answers as those with experience, which means that they were generally informed about the perceived impacts of BIM on designing.

Figure 15 shows the standard deviation in the responses to the same question as previous, but excluding respondents with no BIM experience. It shows that among BIM users, the impact of BIM on ease and joy of working caused most disagreement, whereas the effects on visualisation received similarly positive ratings from all designers.

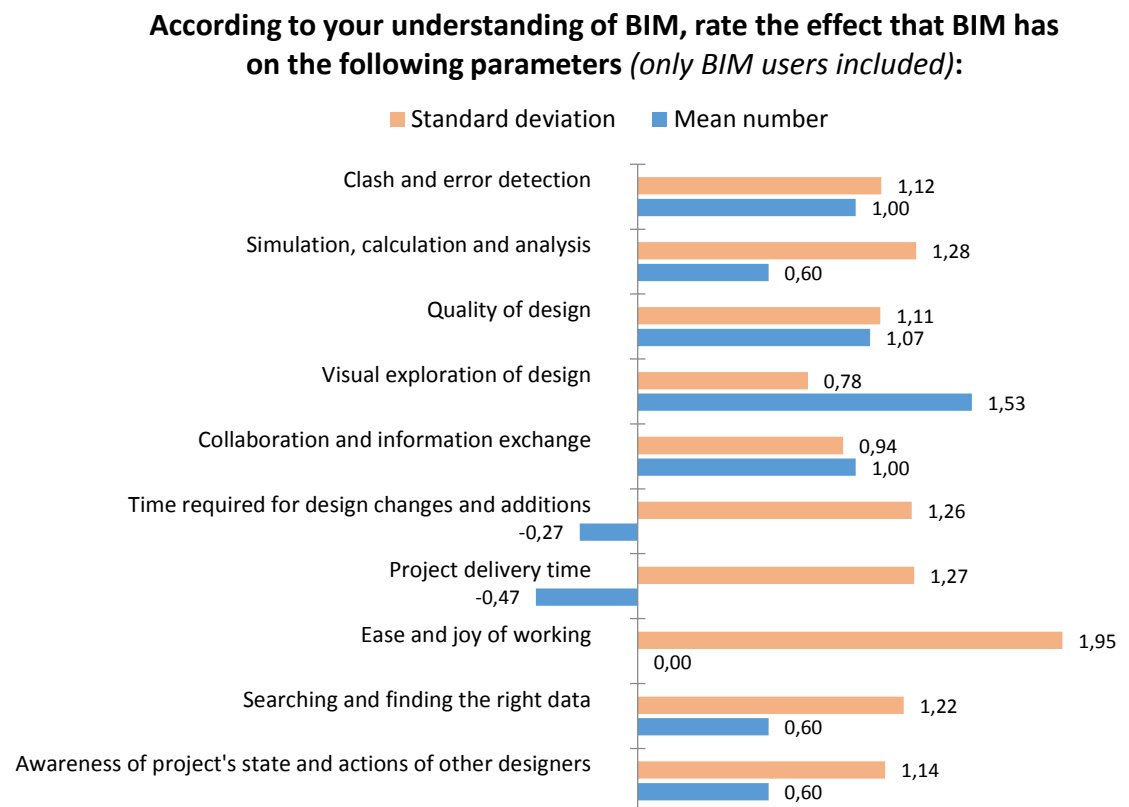


Figure 15: Standard deviations of the ratings of BIM's effect on different aspects of designing by BIM users.

More detailed analysis shows that within the group with experience of 1-2 BIM projects, the impact of BIM on time required for design changes and additions was rated as negative ($= -1,25$) unanimously, with the lowest standard deviation among all groups ($= 0,43$). The standard deviations within groups with different levels of BIM

experience were comparable, supporting the credibility of answers, with standard deviations of the group with no experience being slightly higher for some parameters.

The most experienced BIM users were more aware of different features of BIM and suggested more different features (Figure 16). The figure shows the results on analysis of responses to an open-ended question asked in the early part of the questionnaire. The question is formulated as following: “According to your understanding, what are the most important features of BIM?” The attendees were asked to state 1 to 3 features. When the responses were analysed and combined into the following figure, the answers with identical meaning were counted under same categories, which are listed in the figure.

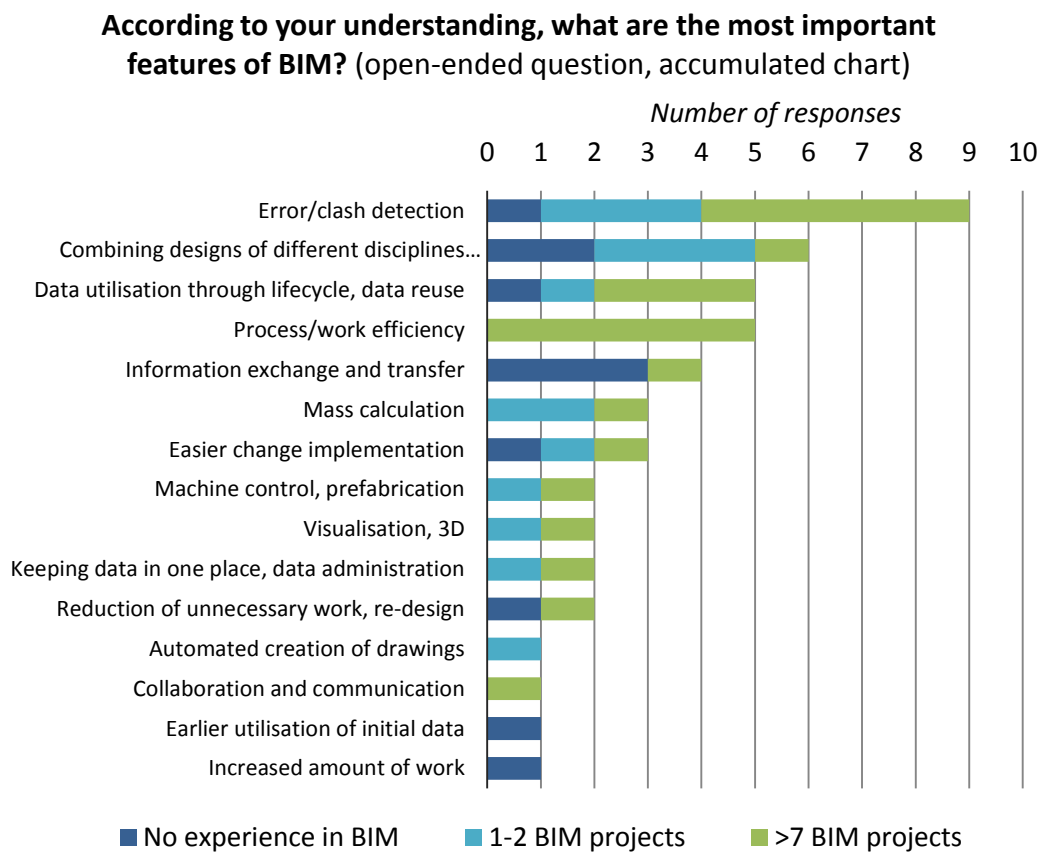


Figure 16: Open-ended question about the features of BIM – answers categorised and arranged in a stacked bar chart.

As the figure suggests, the most commonly recognised feature of BIM is clash detection. BIM experts have suggested higher variety of features and recognised process-related features more than the rest of the designers (e.g. ‘Process/work efficiency’, 4th category from the top).

The figure also suggests that when the categories have similar meanings, BIM users tend to mention more precise and specific attributes. For example, they prefer to state

‘error/clash detection’ over ‘combining the designs together’, and ‘data utilisation through lifecycle’ rather than ‘information exchange and transfer’, although these categories are interrelated (but not equal). Finally, the designers tend to name only positive features, although one designer with no BIM experience have mentioned the increased amount of work as the characteristic of BIM.

It must be noted that the questionnaire relates to the perceptions at the time of the research and not to the case projects. Some of the responses might contain, in addition to existing BIM attributes, some of the assumed or potential benefits that the designers would like to see. However, in order to minimise this possible bias, it was stated explicitly on the workshop and in the questionnaire itself that the designers only needed to describe the current state of BIM in their companies.

In the next open-ended question (figure 17), the designers were asked to state the top three problems that they face most frequently when working with other designers. The question gave a view on the designer’s perception of process-related and collaborative design problems. The results have been categorised in the same way as for the previous figure.

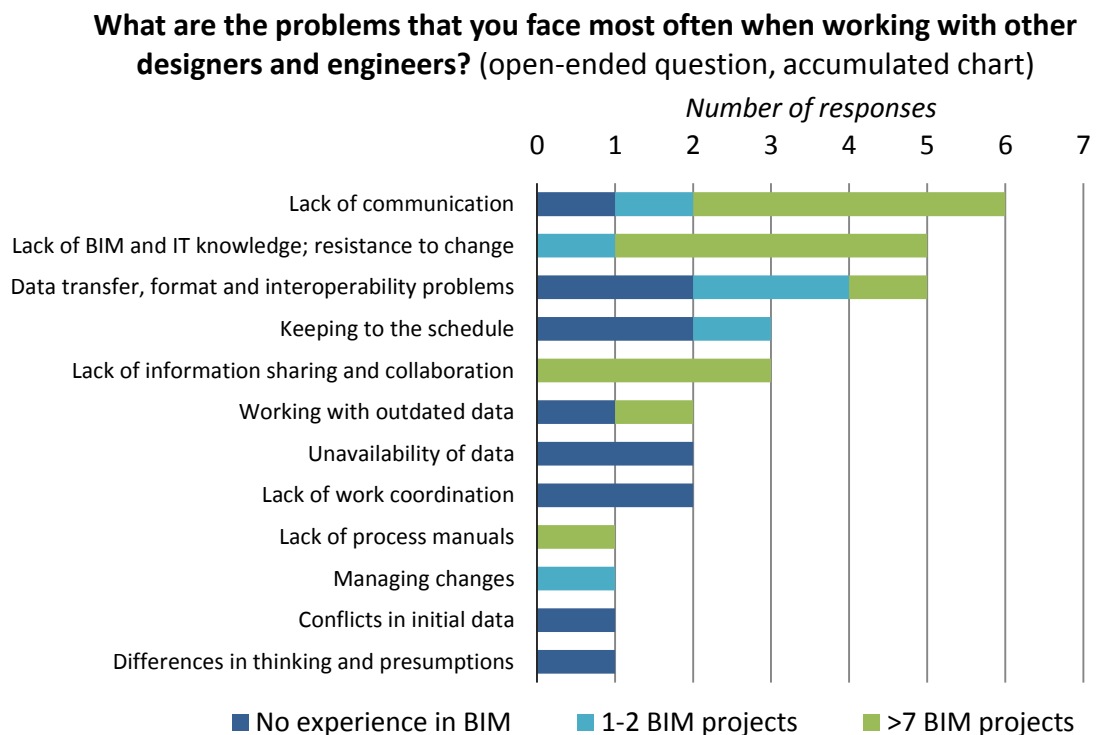


Figure 17: Open-ended question about the problems of designing – answers categorised and arranged in a stacked bar chart.

According to figure 17, the designers with more experience in BIM tended to suggest issues related to IT skills, communication and information sharing significantly more often than designers with little or no BIM experience. However, the latter suggested

more categories for unavailability of data and other data problems. The designers with no BIM experience also stated much more the problems related to scheduling and work coordination.

The figure does not necessarily suggest that in BIM projects some categories of problems occur more frequently or cause more negative effect than in traditional projects. A more probable interpretation is that designers with larger BIM experience tend to deem other problems more important, compared to designers who have been involved in none or few BIM projects. These might be equally the problems that BIM is supposed to cope with, or the aspects of work on which BIM imposes higher requirements.

The presence of some technology-related and BIM-related concepts in a question that does not particularly relate to them was partly due to the workshop agenda, which was communicated to the designers before the workshops, and partly to the fact that a few BIM-related questions were placed earlier in the questionnaire. This influence on answers was impossible to avoid completely.

The open questions ask the designers to mention 1-3 most important issues, which means that the designers, even if they knew about more issues, would state only the most important ones from their point of view. The figures 16 and 17, therefore, do not attempt to show the difference in knowledge between designers (though that may also be reflected in the answers), but primarily the differences in formulation and in *opinions on what is more important*.

The categories of answers listed in figure 16 and figure 17 largely repeat the results of workshop discussions and the problems of designing suggested at the end of workshops, described in sections 4.2 - 4.4. They are also entirely consistent with the problems outlined in the design-related literature that was reviewed in chapter 2, repeating all categories described in the literature.

4.2. Case project A

4.2.1. Description

Case project A was a BIM piloting project undertaken on the general design stage of a road and bridge project. It included reconstruction of a road and construction of bridges. The case design project was special in two ways. First of all, a separate contract was made for delivering BIM. The models were required to be delivered alongside the standard paper-based documentation. The project team that attended the workshop was responsible for BIM project only and included a BIM project manager, a BIM coordinator and two modelling specialists from road and bridge disciplines. The responsibilities of the team during the project included developing the BIM

requirements together with the owner, coordinating the modelling work and creating the BIM deliverables. The case team had limited involvement in actual designing.

The second reason why the project could be considered special was that the initial design stage that preceded the project had resulted in relatively detailed design descriptions, which had taken the initial design almost to the level of detail of general design. The majority of design solutions had already been defined before the project, as well as the approximate corridor in which the road was going to be built; this was related to the fact that part of the road went through the town area with private buildings and land, and negotiations with landowners had to take place during the initial design stage.

The main design project included up to 20 designers. The cost of the design project as incurred by the owner was 500 000 EUR, the estimated cost of the whole project, including design and construction – 50 million EUR. The duration of Case project A was 10 months. The project, both design and modelling contracts, was procured with DBB method.

BIM in the project was implemented on both the preceding initial stage and the general design stage. The first goal for the owner was to test the capabilities of BIM and use the models in construction phase. The created initial and collaboration models were used for clash detection during design. In the conceptual design phase, models were also used for comparing the design alternatives. Finally, the piloting project was used by the owner to develop BIM requirements and modelling standards that could be used in future projects, and to acquire higher expertise in BIM.

As the case project began, the team held a series of meetings with the customer to define the scope of their work and BIM requirements for general design. They started with the initial meeting of the steering group, which included BIM experts, managers, representatives of different technical fields and customer representatives.

After that, the company organised meetings of BIM groups within each of the major disciplines: road design, bridge design, geotechnical design, and road signs and lighting design. The purpose of these meetings was to formulate the modelling requirements discipline-wise. The series of meetings ended with the second steering group meeting that confirmed the requirements and approved the budget estimated for BIM project.

As already mentioned, the customer still required all traditional 2D documentation to be delivered. When discussing the benefits of BIM on the workshop, the project manager and the model coordinator have told that design cannot be made entirely in 3D in any foreseeable future. The reason for this is that 2D representations in many cases have better visualisation properties and are easier to understand and navigate;

they can carry technical data that would be hard to display in a 3D model, and therefore are more usable for detailed design. This was mentioned with regard to both the idea of designing entirely in 3D and replacing 2D documents with 3D models. However, some 2D forms required by today's standards could be replaced by 3D, according to the attendees.

4.2.2. Workshop discussion

The issues discussed on the workshops are presented below. The team members have described the case project and expressed their views on different problems related to BIM implementation. The discussion on the Case A workshops was largely focused on the process aspects of BIM, the benefits of BIM in the case project and in general, and the problems encountered in the case project regarding process, people and technology. The team generally did not discuss designing and issues related to designing because the team was not in charge of the actual design work.

Modelling and data

The BIM project started with preparing the initial model using the data provided by the third party. The initial model included old highway, surrounding structures, terrain model and other major elements of road environment as they were before the construction.

The initial model was used for detecting clashes in initial data and for serving as a basis for collaboration model (the collaboration model included the initial model, so that new designs could be compared to the existing state of the site). The team reported major problems with the quality of initial data, despite the fact that the third party had created their own initial model that should have been used to reduce the amount of errors and inconsistencies in the data. The revealed problems were fixed mainly by the model coordinator and additional data had to be requested too. Company Alpha also had its own old model created during the previous design stage, and eventually it was used too. The resulting initial model was not used by most of the disciplines in the main design project, e.g. the bridge designers only used the standard 2D documentation.

Construction of collaboration model and preparation of BIM deliverables was carried out mostly at the later phase of design project, when the majority of designs were finished. The data from different disciplines was added to collaboration model by the model coordinator each time the corresponding parts of design were ready. Every time, an examination for errors was carried out and designers were instructed what new changes and fixes should be made to the data.

The model coordinator implemented small changes to models to make the designs fit each other in the collaboration model, so that to avoid the lengthy process of sending

instructions to designers and waiting for new data. As the model coordinator told, most of the data delivered by designers had to be modified at least to some extent before it could be integrated. In case of geotechnical design, which was outsourced to a third party, the required changes were substantial. There were two errors in provided geotechnical data that required the designs to be sent back for correction, and many changes still had to be made by the coordinator afterwards.

When describing the modelling issues in case A, the model coordinator stated: “*(There were) problems with geotechnical models, mostly with the quality of the models, so I needed to modify them... Retain walls I made by myself from 3D designs... Foundations of the bridge were all over the place above the ground.*” The team have experienced problems related to data formats and software interoperability, and problems with coordinate systems.

The exceptions from these problems were road design that provided 3D data of good quality, and bridge design, in which a designer qualified in modelling was involved to create 3D models from standard 2D documentation, since the bridge design itself was done in 2D. The manual transition of bridge design to 3D was a difficult and time-consuming task, and the design tool used for the task had limitations with regard to modelling complex geometries. But the created bridge models did not have to be modified by the model coordinator.

The process of revision and correction of collaboration model continued for as long as three months. The collaboration model was also reviewed on meetings. According to the team, the designers did not use collaboration model in their work, so the model was only useful for the client.

Another example of problems faced by the team related to miscommunication of instructions to one of the designers. The specialist took the modelling to a level of detail much higher than that required by the owner. This was unnecessary work. The problem was noticed by the project manager only when the costs related to this discipline (costs were calculated based on spent man-hours) became noticeably higher than they should have been.

Cost estimation and clash detection

Because the main structure of design was defined and decisions on alternatives made in the initial design phase, cost estimation did not play an important role in the case project. It was done in a conventional way, using cost calculation software with manual data entry, and was carried out at the later stage of the project. However, the team believed that automated and more exact cost estimation while doing the design was one of the major potential benefits of BIM.

Clash detection using the models was done by the model coordinator on each revision of the initial model and collaboration model, when new data was added. It was done manually by observing the designs, although some solution for automated clash detection was tested at one time during the project. After revisions the information on the detected clashes was sent for the designers for correction.

Model-based clash detection was one of the main benefits of BIM for the project. It revealed two major clashes that otherwise would not likely be found. One of the clashes, for example, was discovered with the help of initial model and related to pipelines that were planned to be built in the area of construction. The third party that had designed the pipelines was contacted and the conflict was resolved by changing the pipes' location. As the customer reported to the design team, the potential cost of re-work related to the detected clashes exceeded the cost of BIM piloting, making the piloting project fully pay off.

Planning

The Team 1 emphasised the role of the main project manager in planning and coordinating the design, especially at the starting phase. The project was mostly planned by a project manager according to his experience, and the experts from different technical areas were taken one by one to start the work. As the team explained, the design projects cannot involve too many people and spend too many man-hours on planning, as it would increase costs. Therefore, project manager had the leading role in the beginning of the project. The team wished there would be enough time in projects to involve more people in the initial phase. However, in most of the projects it was not possible, according to the team.

In spite of multiple difficulties in modelling, the team was able to meet the budget. The design project was delayed, generally due to the schedule of the customer, and the change of deadline was approved by the customer. According to the model coordinator, this was positive for the BIM project, because it gave more time for modelling.

People and tools

The team has reported on the workshop that communicating the modelling instructions to designers and making designers deliver the right data was a difficult task. The project manager and model coordinator had noticed designers' resistance to change during the project, and were generally dissatisfied with the IT skills of older designers.

During the workshops, the team has mentioned some deficiencies of currently available tools as one of the reasons why motivation of designers to adapt was not high. Some deficiencies of tools could also explain the fact that designers almost did not use the initial and collaboration models. For example, according to the team, the

navigation problems that existed in the software made it hard for common designers to learn how to navigate the collaboration model in order to use it for clash detection. Therefore, clash detection between different disciplines relied largely on the model coordinator. In spite of the improvements, according to the members, “...the software is not yet on the BIM level”, although it was admitted on the workshop that some newest tools might have better functionality than that in the case project.

The team emphasised that the software used at the time of case project did not take into account some of the requirements of designers. As one of the members mentioned, “The developers do not know designing well enough on the grass root level”. According to the team, it was important for software industry to develop BIM tools that would be more usable and would give visible benefits to designers in their individual work.

Sentiment analysis

Figure 18 shows the results of the sentiment analysis for Case project A. As the figure shows, the most commonly discussed issue by the project team is modelling/data, particularly, low quality of initial data and problems with designs delivered to model coordinator during the project. Second and third most problematic categories are designers’ attitudes and IT skills (people), and tools. The dominance of topics related to BIM in the discussion can be explained by the character of the case project and the case team.

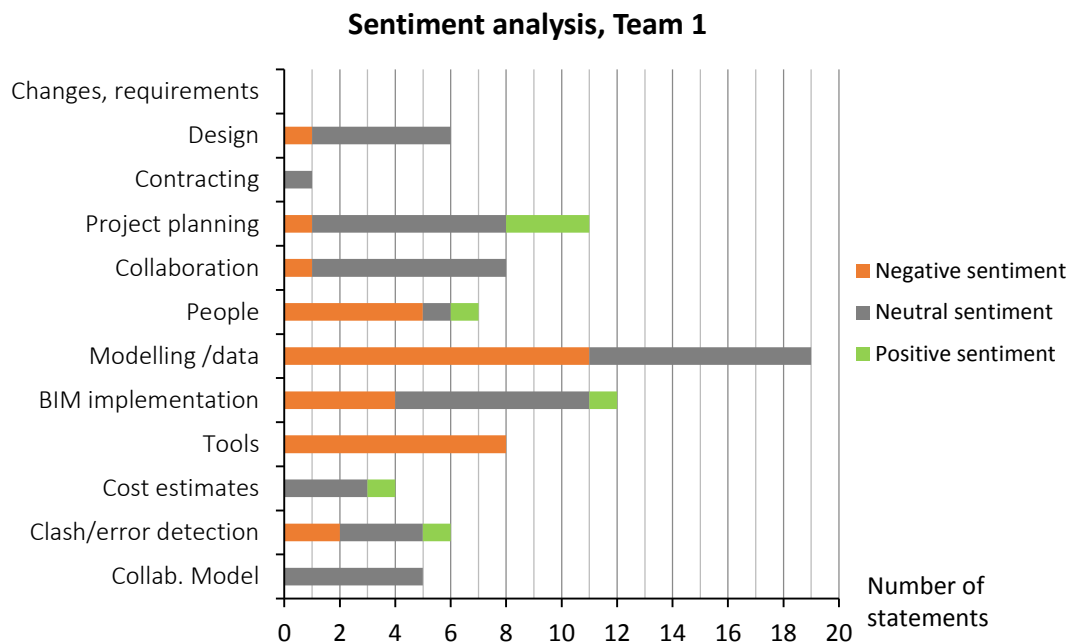


Figure 18: The occurrence of topics and sentiments in workshop discussion: Case A.

The domination of negative sentiments in the topics points at what kinds of problems this team have experienced in the case project and possibly in other BIM projects. The overall picture is especially noticeable when comparing Figure 16 to the Figure 18 that represents the Team 3, which was involved in BIM project Y and included experts with comparable level of BIM experience, but was more positive in the statements. These results do not suggest that BIM did not have value for the Case A or that BIM in general was perceived negatively - this would contradict the team's statements and the questionnaire results. Rather, the figure suggests that the team has acknowledged the difficulties that affected their work in project A, particularly on the process level.

Summary

The results of the Case A analysis outline that the team of BIM experts in the case project faced numerous problems. The discussion with Team 1 revealed substantially more negative sentiments than the discussions with Teams 2 and 3. The following issues are perceived most negatively by the team members:

- Low quality of initial data required correction and completion efforts
- Resistance of designers to adopt new methods and comply to guidelines
- Designers' lack of software skills
- Shortcomings in data provided by designers and third parties required comprehensive correction
- Capabilities of tools were 'not on BIM level'

The problems related to working with designers can be attributed to the knowledge gap between BIM experts and new BIM users (most of the designers are either new users or do not use BIM). The questionnaire has already shown that the new users of BIM are prone to view BIM more negatively and see it as more time-consuming, since they do not have enough skills.

In project A, one of the facilitators for the division between BIM experts and common designers was the fact that modelling was largely disconnected from the design process. This division was even fixed in the contract. Model integration and correction mostly relied on model coordinator, and the BIM-team had to deal with instructing designers on modelling and corrections. The team agreed that the designers in the project "followed instructions at most".

The diagram of the project showed that the project correction and completion phase, which was carried out after most of the design work was finished, took as long as three months to complete. This might suggest that modelling was in some ways a bottleneck for project delivery, although this is hard to verify. The benefits of BIM for collaboration were not realised as the designers did not use the collaboration model, and the model was mostly created at the late phase of the project. Having modelling

and designing in the same project, having one project management team for the whole project and “designing by modelling, from day 1” was mentioned on the workshop by the team members as something they would like to look for in future projects.

Despite the problems, the piloting project was beneficial for the owner. First of all, the owner reported that two clashes identified during the project using the initial and collaboration models could cover the cost of the whole BIM piloting, since they constituted major risks for construction. Secondly, the project involved developing BIM requirements and guidelines, and has contributed to BIM expertise of both the client and the design company. As the team reported, the expertise of Company Alpha in BIM initially exceeded that of the client, and BIM experts from the company had a major role in formulating the BIM requirements.

In general, the team was positive about BIM as a developing technology that has a potential to facilitate the work of design companies in infrastructure sector, although many prospect benefits of BIM were not yet realised. The team emphasised the role of process, people and management in achieving improvements in the sector, and their primary role in successful technology change.

4.2.3. Problems of design projects, Team 1

At the end of the workshop, the team was asked to select the most important problems that the designers face in their work. The problems were largely suggested by the previous discussion, but do not refer to only the case project. After the two key problems were selected, the team was asked to name the causes for these problems using the Ishikawa diagram as an aid tool. The two problems and their causes stated by Team 1 are:

- *“Lack of collaboration*
 - *Design and modelling is separate*
 - *Lack of tools for data management*
 - *Old habits of designers*
 - *Lack of IT skills*
 - *Lack of information sharing*
 - *Collaboration model is under-used*
- *Faulty initial data*
 - *Lack of interoperability*
 - *Lack of common formats*
 - *Lack of quality checking*
 - *Lack of process guidelines”*

The named issues relate to the same categories as those that caused the most negative sentiments during the earlier discussion: resistance to change among individual

designers and problems with modelling and data, such as lack of interoperability. Particularly important is that the discussion of technology goes beyond BIM: the team mentioned the lack of data management tools as one of the problems. In Case project A, project bank was used as a tool to share finished designs; however, most of design information was exchanged through internal project drive and even email, which could sometimes lead to delays in data delivery, dispersal of information between many sources and the inability to find the right data when required. It was not clear from the discussion how high the degree of impact of this problem was on the team's work.

In general, the central topics of the Case A discussions were modelling, information process and communication. The relation between process improvement and technology improvement was constantly mentioned by the team members. The members tended to view process as the primary issue, and technology as the facilitator of design, collaboration and management. As the project manager mentioned, "BIM has much potential to make things more effective, but the key is in the process and the people running this process, and the key is always communication, and knowing in advance what is supposed to happen. BIM is a tool; it can be a tool to support project management."

When describing the hypothetical 'ideal' project, the members stated the following principles:

- *“Right and appropriate tools for design, project management and collaboration*
 - *Everybody knows how to use them*
 - *Software are easy to use*
- *Clear guidelines both in design company and client organisation, and commitment to guidelines*
- *Communication*
- *Right attitude*
- *Right people*
- *Goal-oriented customer*
- *Customer who has knowledge of BIM*
- *One project manager and one project (design and BIM are not separate)*
- *Modelling starts from day 1, design is done by modelling*
- *Collaboration meetings with all disciplines every two weeks or when needed*
- *Accurate schedule*
- *Initial data received in the right format*
- *Efficiency: everybody knows what they are doing (right things in right order)*
- *Critical self-evaluation after every milestone/project/design stage*
- *Continuous development of knowledge and process; systematic learning”*

The team's vision of an ideal project highlights some of the same issues as the designers have expressed during the workshop, and, as the following sections will show, largely repeat the issues that other teams participating in the research have told.

In addition, the project manager expressed his opinion about the large size of BIM piloting projects. According to him, implementing BIM in a large project makes it difficult to achieve many benefits and is not as effective as investing the same money in a smaller project could be. Therefore, according to his opinion, public owners need to conduct smaller piloting projects where it would be possible to reengineer the entire process and take it to the actual BIM level.

4.3. Case project B

4.3.1. Description

Case project B was a conventional design project for road reconstruction. The project included the increase in capacity of an existing road and the construction of new interchanges. Case B was a road planning project. Road planning is commonly a first stage of road design process in Finland, and when it is, it incorporates both the initial and general design. It results in the development of a road plan – a set of documents including maps and cross-sections that has a medium level of detail and is used as input data for construction-level design.

Like in all case projects, DBB procurement method was used in Case B. The ownership was divided between two public authorities, and a number of other stakeholders (e.g. other facilities in the area of the site) participated in the project imposing extra requirements and providing the initial data. The cost estimate for the construction work was 42 million EUR, which is comparable to Case project A. The cost of the design project was 703 000 EUR and the duration was 18 months, which is more than in Case A, and is related to the fact that project B comprised both the initial and general design stages.

4.3.2. Workshop discussion

The content of the discussion with Team 2 significantly differed from that with the team 1. Team 2 discussed primarily the evolvement of design and the common practice in traditional design projects. The members explained in detail how the design is developed by technical areas and how the requirements and cost restrictions are embodied in design. The effect of changes in requirements on the design process was also discussed.

Another group of topics discussed during the workshops was related to planning, coordination of resources and coordination of work between technical areas. The designers described problems that stem from the constant lack of resources and

unpredictability inherent in project-based activities, as well as from the common shortcomings in the industry practice. The discussion also included the issues related to communication and data exchange, and outlined the existing approach to collaboration in the traditional projects.

Design and data

As the team described, the case project started with the initial data gathering and meetings with owner representatives. The initial data included terrain data, older geotechnical data, drawings of existing road, structures and engineering systems, land use plans etc. Requesting for additional data was mostly the responsibility of individual designers. Additional geotechnical surveys were carried out by the company and the results were significantly different from the existing data.

The design process in road projects is generally point-based. The design is defined by existing environment and the planned road capacity, which is the critical requirement for design. This requirement is communicated in middle-term and long-term traffic forecasts. The forecasts are used by designers to make traffic simulations, which determine the road geometry, number of lanes and types of ramps and intersections.

Traffic simulations in the Case B were done using the simulation software and the proposed traffic solutions were assessed by road designers. The alternatives, when there were such, were shown to the client. This process of conceptual design reiterated until basic plan of the road was created.

The team members told that there were no problems related to the quality of initial data. According to them, the more usual problem related to initial data in their projects is incompleteness: some data can be missing and has to be requested again.

Project bank was used to deliver the finished designs. The data was exchanged internally using the project drive. The designers were instructed to always save the updates to the drive, instead of storing them on computers. As the project manager have said, the designers should not (and in most cases do not) keep the newest files on their own computers, because it can disrupt the work of other designers by making them use old or incorrect data.

Keeping all files up-to-date was considered necessary by the team; it ensured that all designers and the project manager had the correct and latest information. However, as the members have told, in some cases a designer is unaware that a change has occurred in another person's work that affected his own work. For example, if the change is mentioned on a meeting and the designer affected by this change is absent, the issue might be forgotten inside the meeting notes and not communicated to the designer, causing him to unknowingly use the incorrect data or assumptions, and eventually do extra work to correct the designs after the change is noticed.

According to the team, working with outdated information is nevertheless a rare problem because both the creator and the user of data usually check that it is up-to-date (the user sometimes have to ask if a shared file is newest). As the members said, it is always important that the designers discuss their work face-to-face, not only by sending the drawings, because there are some issues that cannot be overlooked without direct communication.

Requirements and changes

One of the problems in the case project was that the scope of design was not defined before the project, thus the pre-design was done partly after designing had started. Changes in the scope during design required additional orders from the owner. Normally, if additional work is required due to change of customer requirements or change in proposed solutions (e.g. construction of additional bridge), the deadline for the project can be moved under an agreement with the client. In the case project there were additional orders but the schedule was not changed. As the designers believed, the fact that pre-design overlapped with road design was beneficial for the quality of developed solutions.

According to the team, the general impact of design changes is the highest for disciplines that start later, such as bridge design, because they often have to work with partially ready data from road and geotechnical design in order to meet the schedules. This is consistent with the literature reviewed in section 2.4. The changes in the data are more likely to occur when designers work with data from tasks that have not been completed. These changes in data can make some of their designs become obsolete and result in re-design. As the bridge designer explained, many years ago it was possible for bridge designers to start when the preceding design tasks were completed, but nowadays it was not possible because the schedules became narrower.

Cost estimation and clash detection (conventional)

The cost of design options was assessed whenever any alternatives were considered. In the case project most of the alternatives related to geotechnical design. Cost assessment was done using specialised software, with manual data entry.

The costs in projects are usually calculated only for the fragments of design that are affected by the alternatives. For example, when a new bridge option requires different road geometry, all impacts of this option on road construction costs are also included in calculation. According to the designers, because the costs are calculated by the specialists from the corresponding technical areas, it is important to agree who calculates what so that same costs are not calculated twice.

Clash detection in the project was carried out in a traditional way. This means that designers from different technical areas had to exchange and cross-check drawings and conduct face-to-face meetings in order to ensure that designs fit each other. Designers

usually review their drawings in pairs by comparing them against each other, placing one drawing on top of another in design software. At the end of projects overall clash detection is usually done including all disciplines.

In the case project face-to-face meetings were easy because all designers worked in the same office. According to the team, face-to-face meetings for ensuring design concurrence are easier for those designers who work on the same floor than for those on different floors. Regular project meetings with the whole team also help clash detection: the meetings make designers aware of what is happening in other disciplines and provide them with information on where to look for clashes.

Besides finding the clashes between disciplines, the designers have to ensure that their own designs are correct and consistent. The designers create many cross-sections, including alternative solutions that are not necessarily included in final design. When working with 2D, the designers have to move between different projections, from XY to XZ to YZ, and make all views consistent with each other.

Project planning and collaboration

The designers had substantial impact on planning the work, although the project manager had a leading role in planning. The designers made their input in scheduling by giving estimates of when they could start and how much time they needed to complete their tasks.

As the team members explained, planning in the beginning of the projects is usually done forwards, so that the tasks are arranged starting from the beginning; later, when the content of work is known and the deadlines are set, the tasks are rather planned backwards starting from deadlines. This was reflected in the case project's time schedule, in which all tasks started at different points of time but finished at the same time. A common problem for late design disciplines, such as bridge design, is that sometimes they do not have enough time to finish their work before deadline because previous tasks has taken too long and has delayed the start of their work.

In addition, later disciplines such as bridge design have to take part in early stages of design when their participation affects the earlier disciplines. Their involvement in early design phase is needed in specific cases, where multiple options are available and where some problem or risk exists regarding their technical area. For example, the requirements of bridge design can affect the road design: if one road goes above the other road in a too narrow angle, specific road geometry or other solution may be required to ensure that the bridge can be constructed. This way the requirements of later disciplines are realised in earlier phases of design, to ensure constructability.

Generally, the team members mentioned that virtually all disciplines are connected and can have some impact on each other. The team emphasised the importance of communication and regular meetings in projects.

In the project meetings were held monthly, in order to review the designs and discuss the progress with the owners. On these meetings the team discussed what had been done and what should be done before next meeting. The team discussed changes and provided information for the customer to make decisions. On each meeting, the agenda and date of a next meeting were set. In addition, the company held special meetings with other stakeholders such as public organisations, land users and third parties (e.g. meetings with electricity grid operator). A public meeting was held to present the design to stakeholders and public.

According to the team members, it is usually difficult to plan the projects and coordinate the work. Designers work with many projects at the same time. The schedules are usually not precise and are done according to experience. The intensity of work within a project can change in relation to other ongoing projects: designers generally start spending more time weekly on one project compared to other projects when the deadlines are approaching. The members have stated that the work for each project becomes more intensive before each project meeting, and the intensity generally increases towards the main deadline.

There is no general schedule that could combine schedules of all projects of the company. Different projects are coordinated on high level by project managers, but this coordination is limited, even though they might share the same designers. Usually the company competes for all tenders, even though the designers might be occupied with existing projects. If two projects have to be done at the same time, the more important project is prioritised and the less important one has to be delayed. The tenders and projects are seasonal, because designs usually have to be ready in spring before the start of construction season.

The designers have repeatedly mentioned that their time is always scarce, and it is usually very hard to keep to the schedules. Because of that, they cannot invest too much time in planning in the beginning of projects. In fact, designers are always occupied with their work. According to the project manager, planning and project management is much more basic and simplistic in infrastructure engineering than in other industries, and “schedule is only an estimate” in infrastructure design projects.

Sentiment analysis

The analysis of textual data from the Case B workshops revealed substantial differences from the Case A (Figure 19). The number of negative statements in the discussion was considerably lower than in the previous case. People and tools – the

topics that had caused overwhelmingly negative sentiments in Case A – were almost not discussed in Case B workshops. The amount of neutral statements was high in project B.

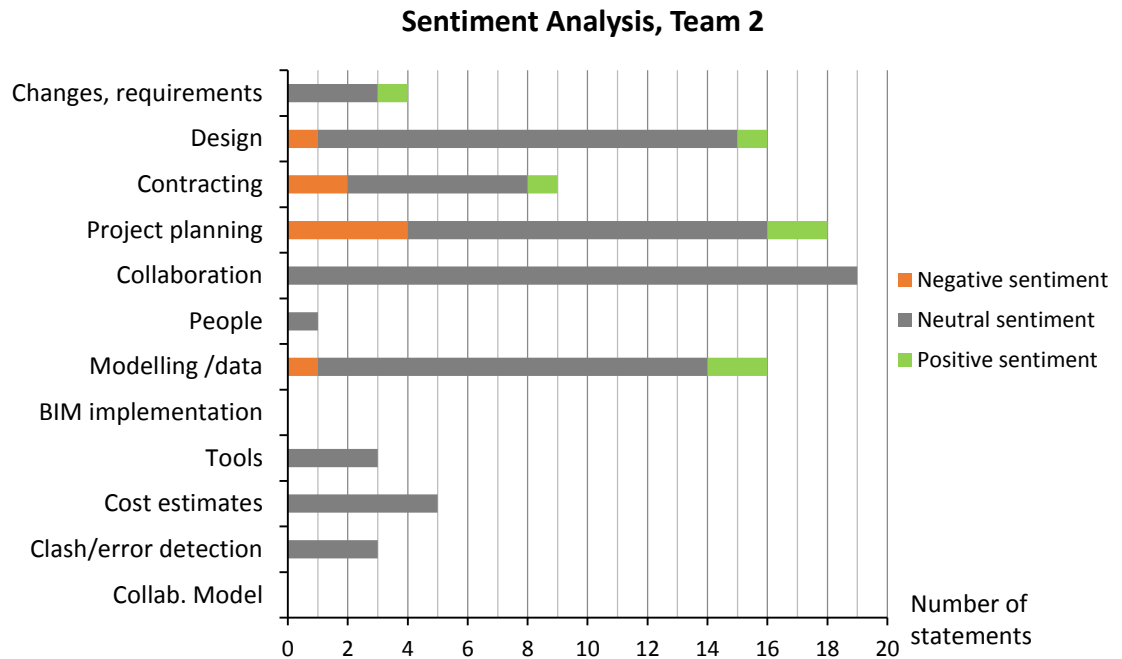


Figure 19: The occurrence of topics and sentiments in workshop discussion: Case B.

The discussion was not focused on modelling or technology, although computer-aided designing and design data were among the discussed issues. The most frequent topics were collaboration, project planning and design. Topics exclusively related to BIM were not discussed. Even though BIM was mentioned in the workshop agenda, the members of Team 2 had limited knowledge about BIM and the discussion was focused on other issues.

Summary

The study of the case project provided a comprehensive view on design practice in the infrastructure sector. Process-related and collaboration-related issues dominated the discussion. The discussion had the lowest number of critical sentiments, and many issues that caused the criticism in case A were not discussed by the case B team.

The traditional design process included a number of good practices, such as systematic information sharing and involvement of designers in planning. However, the team outlined a number of problems in design activity, which largely mirrored the conceptual problems of collaborative design identified earlier in literature review.

The issues of project planning and resources draw particular attention. The limitation of resources and common industry practice was viewed by the team as the main reason

for inaccurate and basic project planning, both in terms of scheduling accuracy and definition of design content in the beginning of the project.

Another planning-related problem outlined by the team, which has also been mentioned by Team 3 in the following case, is that designers participate in many projects at the same time. There is no general schedule that could integrate all project schedules in the company. The Team 2 members suggested that right project management tools and software could possibly help planning and coordinating the project, but such tools were not available. The members repeatedly mentioned face-to-face communication, work coordination and systematic data handling as important facilitators of efficient design process.

4.3.3. General problems and the ideal project – Team 2

The first problem selected for discussion was management of change in projects. The changes in schedules were in focus of discussion, but changes in work content and design were discussed too, as they typically affect the work progress and might cause delays.

According to the team, possible changes are often not considered by project management and their impact is not taken seriously. When designers start the project they know approximately when they have time for it with regard to other on-going projects. A change in the schedule that moves the start of the tasks to the points of time when designers are busy with other projects means that at least one of the projects has to be delayed.

Every change can cause a chain reaction, for example, a delay earlier in the project can affect the bridge design, and the designers will have much less time to complete their work. If the possibility of delay is not thought in advance and the bridge designers do not have available resources when needed, the project will likely miss deadlines or the bridge designers will have to compromise on other projects.

According to the members, changes always occur and are not always possible to oversee, but a project team and a project manager should never stop thinking of risks and always consider what is going to happen next, in order to take preventive measures. When stating the issues that can cause problems with change management the team listed both communication problems and technology. Some points related to the problem of checking other disciplines' work and achieving awareness of the disciplines' progress:

- *“Change management problems*
 - *Lack of software skills*
 - *Too tight schedules*

- *Lack of communication*
- *Lack of cross-checking between disciplines*
- *Designers use different formats/templates*
- *Customer has too tight decision schedule”*

The last issue on the list relates to restrictions that the customer’s decision-making schedule imposes on projects. Usually no changes in decision-making schedule are accepted by a customer, so in case of delay in a project, the quality of design would be compromised rather than the customer’s decision schedule. For example, in one of the projects the client was ready to give up some of the previously required design documentation in order to preserve the dates of decision making.

The second problem related to project planning. According to Team 2, project planning is done on too high level, meaning that planning is very general and there is not enough accuracy:

- *“Project planning is done on too high level / not accurate*
 - *Amount of resources hard to estimate*
 - *Lack of tools (e.g. software) for project management*
 - *Old practices of planning*
 - *The inputs from disciplines are inaccurate*
 - *Not enough information from contracting phase”*

As the team members said, schedule is mostly an estimate. Typically, when different design disciplines provide their design plans and time estimates to project managers for making the schedule, project managers cut the suggested timeframe by 30% because the timeframe is too long and makes the project too costly. After that, according to Team 2, “nobody plans how to design it with only 70% of time”.

The members have also mentioned the lack of tools for project management. This problem might have several reasons: the company not using the tools, the project managers being unfamiliar with available tools, or existing project management software being inappropriate for the needs of infrastructure design projects. The reasons were not broadly discussed with the team.

The last problem suggested by the team members was not having enough resources in the beginning of design projects to ‘design the design’ – to define the design content and formulate the requirements for design process and output.

- *“Not enough resources for designing the design*
 - *Industry practices do not support proper project management*
 - *The design detail/accuracy should be decided in advance*

- *Project organisations grow large but do not have general/master planning*
- *Competitive bidding prices do not allow designing the design*
- *Customer's schedule has unrealistic expectations*
- *One person does not have necessary skills and knowledge to design the design*
- *There is a tendency in consulting firms to pass the extra work to other consultants when the schedules are too tight*
- *On the tender stage it is not possible to plan the tasks of different technical areas, or the need for such planning is not understood"*

The problem is related to the fact that the design costs accumulate with the man-hours spend on the work, and the company is interested in spending as little time as possible on every task. The lack of time is enforced by tight schedules set by the customers and the fact that there are many projects that designers have to deal with at the same time. Therefore, design companies strive to start design work as early as possible, and they prefer to invest minimum time in planning in the beginning of the projects.

Designing the design is, therefore, an instance of inaccurate and basic project planning that characterises the industry, according to the team. Planning in general, time-wise and content-wise, largely relies on project managers, and the input of disciplines is minimal and inaccurate. All three problems selected by the team relates to planning the design work and organising the resources. The problems of planning were also mentioned by the Team 1 as described above, and were broadly discussed by Team 3 on Case X-Y workshops.

Finally, the principles of ideal project outlined by Team 2 included the following points. Five of these points are the same as suggested earlier by Team 1 (marked with an asterisk):

- *"Planning the process beforehand**
- *Adequate schedule**
- *Keeping organisation as thin as possible*
- *People work only on this project*
- *People do not change during the project*
- *Finishing phase of the project is maximally short*
 - *Designers start delivering finished work to themselves early enough*
- *Regular internal meetings**
- *Fast and comprehensive updates when necessary*
- *Organised information exchange*
- *Sufficient resources*
- *People are committed**

- *Owner is skilled and experienced**”

The project manager wished that the organisation in design project was kept as thin as possible, so that less people are involved in design project and can focus more on one project. Ideally, the manager said, each designer should work only in one project. The manager also told that the completion and delivery phase of the projects that usually takes place after most of the design is done should be kept as short as possible.

4.4. Case projects X and Y

4.4.1. Description

Case project X was a traditional railway renovation project carried out by Company Beta. The project took 14 month, from spring 2012 to summer 2013, and also included building a 3D model for machine control systems, contracted at the late stage of the project with a separate order. Project X was a general design project.

Case project Y was an ongoing railway project in which Company Beta was participating at the time of research. The project included reconstruction of existing track and construction of the second parallel track, and the design phase utilised BIM. The project was carried out by several design companies, and the area of the project was divided between them in equal parts. One company had already completed the designing, and the other companies, including Company Beta, had recently started the project.

Both projects X and Y were carried out by the same project management team – Team 3, which included the project manager and leading designers of major disciplines.

DBB contracts were used in both case projects. In Case project Y, BIM was a part of the contract for Company Alpha, and was not contracted separately from design. The designs delivered by all companies were going to be integrated in collaboration model by Company Alpha.

The two case projects were not comparable because project Y included considerably larger amount of work (construction of new track) and more resources were dedicated to the project, since the schedule for the project was set very tight by the customer. According to the team, the designers in project Y had to focus on the project and spent most of their weekly work hours on it, whereas in project X the timeframe was longer and the work was much less intensive, letting designers to focus on other projects. Project Y also involved much higher number of designers. That explains why, despite substantially larger amount of work, the project was scheduled for 13 month, against 14 month in project X.

BIM in the project Y was required by the customer: the organisation is seeking to improve its own skills and efficiency. But same applies to the design company as well. The owner and Company Beta developed and tested modelling guidelines. The main purpose of BIM guidelines was to make the models usable in subsequent AEC phases, particularly in construction. The BIM guidelines used in the project had to be always considered by designers during modelling. However, in all BIM projects clients still require all traditional 2D documents to be delivered.

As the team said, most of the design software they used in all their projects allowed 3D visualisation, thus, when it comes to the benefits of BIM, the company was mainly looking for other benefits such as model-based cost estimation. In project X, the company was ordered to create a model for machine control systems, which is also attributed to BIM, although the major design project was traditional.

No collaboration model had been created in project Y by the time the workshops were held. Firstly, by the time of the workshop no finalised designs had been submitted to make the collaboration model – the disciplines were in the middle of their work. Secondly, the company was looking for IT solution for collaboration model, as the access to collaboration models was difficult in earlier projects for one of the offices of the company due to network limitations.

4.4.2. Workshop discussion

The highlights of the workshops, presented below, will combine discussions that took place on workshops for the cases X and Y, making necessary distinctions only when necessary. Presenting the cases X and Y together is required because the projects were made by the same project team, and hence it is often impossible to attribute statements made on the workshops to one or another project exclusively. Separating the workshop data between the cases would also be methodically incorrect, since the designers, when describing the past events, are prone to a recall bias and might describe each of the projects through the prism of their general and more recent experience (project Y was on-going at the time of the workshops, and project X ended a few years before).

Design, modelling and data

Most of the design software in traditional projects provides some 3D view; however, there are differences between BIM process and traditional process. The team involved in the cases X and Y has been asked to describe what the role of 3D and 2D designing in their work is and how these two modes of work change during the design process, both in BIM and traditional projects.

As the members have told, in all contemporary projects the design software uses some 3D view on the background. In both types of projects, the designers use terrain model and geometry as the input data, and first work with 3D. Then they move to separate

cross-sections for detailed design, and work in 2D to draw the cross-sections and maps. They use the 3D model to observe the designs. Because 3D view does not allow seeing the design in detail, the detailed design has to be carried out in 2D.

The main difference between traditional and BIM projects is that in traditional projects some designs are done entirely in 2D, and final output is always in 2D. The information is transferred in 2D to disciplines that generally work with 2D (such as bridge and geotechnical design) even if a designer sending this information used a 3D view in his work. In BIM projects, there are specific requirements for the model and the process differs from traditional designing in certain ways. Design is done by modelling always with 3D output, and 3D data is exchanged and added to the collaboration model.

As the team stated, in the future at least some of the documents could be delivered only in 3D. According to the team, one of the reasons for why all traditional 2D documentation is still required is that not all construction companies have BIM capabilities and could use the models.

In both Case projects X and Y the designing started, similarly to the project B, with gathering the initial data and evaluating the need for geotechnical research in field. After geotechnical research was carried out, additional research had to be done again. In total, ground surveying continued for 6 month. The team also reported problems in terrain data provided by the client that explained why extra land surveying was needed.

The designing in project Y started with track geometry design; project X was only a reconstruction project and did not require changes to geometry. As the team described, in railway projects the track geometry determines overall design to a very large extent, and is required by all disciplines in order to proceed. In Case Y the geometry design was done at the same time for all project areas, and all companies could use it as input data. The companies then had only to match the areas where their designs met.

The railway and geotechnical design usually start at the same time, and typically ground research is carried out for geotechnical design, as it was done in both Case X and Case Y. Due to territorial scale of typical railway projects, geotechnical design plays a very important role in railway engineering. Like in road projects, geotechnical solutions are required in particular locations of the railway where ground reinforcements are needed, for example, areas with soft ground. The track designers draw cross-sections of the railway each 20-40 meters and in specific places where required, and a longitudinal section that shows the cut of railroad structure along the track.

As the track design is developed, drainage systems are designed to ensure sufficient water flux and protection from flooding along the track. Bridges and electric systems are other large disciplines. As the team described, “every discipline develops more and

more accurate design throughout the project, and the designs have to be discussed and matched continuously, unless the project has a freezing point at which some tasks have to be completely finished.”

Changes of requirements

In project X the railway had multiple crossings with roads, and some of the crossings had to be changed to bridges or underpasses in order to increase the road and railway capacity. The changes in some bridge solution initiated by the customer required changes in the schedule and additional work order, which made the project longer. Because such changes are approved and paid by the customer they do not constitute a problem for the design company.

The change in project X was related to the fact that the bridge structure initially required by the customer was not possible to be build, because it would have required the existing road traffic to be substantially cut during the construction. This was prohibited by the road traffic authority after the designs were sent for inspection in the middle of the project.

Generally, the problems in customer requirements often cannot be noticed early enough because the tender documents lack detail, and because the designers do not have enough time in the beginning of projects to look for all possible inconsistencies. That is why in case of problems with requirements, customer has to make additional orders. This may actually be beneficial for a design company but can extend the project timeframe and does not deliver additional value to the customer.

Cost estimation

In railway projects in general cost estimation plays an important role, especially when applied to geotechnical solutions and track designs that determine the amount of excavation work and material required for construction. As the members of the team said, BIM can help saving construction costs by enabling the comparison of costs of different options. For example, the designers assess the impact of different ground elevations and calculate masses to find out the impact on construction costs. In the case project, models were used for cost estimation. According to the team, the estimates from the models were more precise than traditional cost estimates.

Cost estimation was done for all design alternatives, always considering all elements of designs which were affected, similarly to cost estimation in project B. Construction costs played a critical role in shaping the design; whenever a cheaper alternative was found it had to be considered. The team stated cost estimation as one of the major benefits of BIM in their work.

Clash detection

Clash detection in railway projects, according to the team, is mostly relevant for checking the design of tubes, wires and similar objects at the end of the project. Since project Y did not have a collaboration model by the time when workshops were carried out, no model-based clash detection was carried out between different technical areas by that time.

In project X designers had to match their work in a traditional way – with the help of meetings and communication. As the team have explained, it is a good practice when the succeeding discipline sends their designs back to those who have provided the input data, but in the case project this was not done. Clash detection in project X, as described by the team, was done similarly as in the Case project B.

Planning

The work in AEC firms is seasonal and design projects are usually finished right before the start of construction season. The deadline for both project X and project Y was determined by the dates when the construction work had to be put on tender. The projects were generally scheduled backwards starting from the final deadlines, and this was reflected in the project schedules. Because Case project X was a renovation project, it did not require a long period of initial designing. The design disciplines could start almost simultaneously: track design, geotechnical design and bridge and structures design.

A difficulty related to planning and management that has been mentioned on the workshop is inability of managers to track the work progress within disciplines to know exactly how far the work is. The work progress can only be seen when the designs or versions of designs are ready and shared. Other designers also cannot see the progress until the designs are shared. A typical barrier to sharing the designs is that designers do not want to publish work that is too unfinished from their point of view, which can be explained by their wish to prevent other designers from taking the risk of working with unfinished data, but may also have social and psychological rationale.

The difficulty of tracking the work progress and achieving awareness of design means more coordination has to be done face-to-face. The designers also told it is easier to track the progress when a large design task is split into smaller tasks.

Because designers normally work with many projects at the same time, one project in a designer's portfolio of ongoing projects can be active throughout a long time, but the designer can spend only several hours a week on this project. This means that the time schedule only reflects the dates when the task has been started and is supposed to be finished, but does not reflect the actual amount of work. Looking at a project schedule

it is impossible to say how much time the designer works on the project: 4 days a week or 4 hours a week.

It is not possible to oversee the amount of work that has to be done within a task, or to say exactly how much of the task have been completed. Therefore, planning is done according to the experience and project managers have to compromise on the least important projects and sometimes re-arrange the resources in favour of more important ones in order to meet the major deadlines. It is important for project management that designers provide information about their work and give time estimates throughout the project. This, and the split of large design tasks into smaller tasks mentioned above is realised in Last Planner system of production control.

In project X, the designers had relatively limited participation in planning, and planning was carried out similarly to case B. The Case project Y used the first phase of Last Planner to facilitate coordination and control. The team held meetings every two weeks to review the schedule. The design tasks, such as track design, were split into smaller tasks that could be written on post-it notes. Designers themselves have decided the deadlines for the tasks, according to their estimates on how long it will take them to complete the tasks. The notes were then put in an order and written down in a spreadsheet tool.

Nobody could leave the meeting without agreeing on what the schedule is. If someone could not attend, he was represented by the project manager. In that case the tasks of this designer were marked with red colour to make everyone see that this hasn't been checked.

Data deliveries between designers were reflected as separate tasks, and that is how the connection between disciplines was reflected in the schedule, for instance, when one task had to be finished in order for the other one to proceed. Every designer had to know what they needed from other designers and had to put it on post-it notes. As the project manager described, it was difficult for the designers to say what data they need to proceed in their work. The system required designers to change their way of thinking: they had to understand their own work process and the place of other designer's inputs in their work, instead of just being given the data.

On the last planner sessions the team also discussed the 'just-in-case' time buffers: the designers challenged each other to find out if there was any way of making the tasks shorter, of reducing the suggested timeframes. As the project manager told, the method gave certain positive results in terms of planning and also helped the designers to understand each other and interrelations between each other's work better, although there were difficulties and the benefits were not very straightforward.

Tools

One design software for road design was demonstrated on the workshops. The functionality included the dynamic 3D view, the possibility to see foundation inspections and to observe cross-sections in any place of the road. 2D documents could be produced from the model automatically. The members expressed certain dissatisfaction with the fact that available software for railway design and other disciplines did not have the same level of functionality, according to their knowledge.

The designers also mentioned that their work was affected by interoperability problems and problems with coordinate systems and file formats. The team have shown a variety of specialised commercial and open-source software that different disciplines could use in design projects. According to the team, the variety of software and the lack of interoperability made data exchange between different software problematic. However, interoperability problems were affecting their work much less than several years earlier.

Sentiment analysis

Figure 20 presents the results of sentiment analysis for workshops with Team 3. The sentiment analysis for the cases X and Y was done for two projects together.

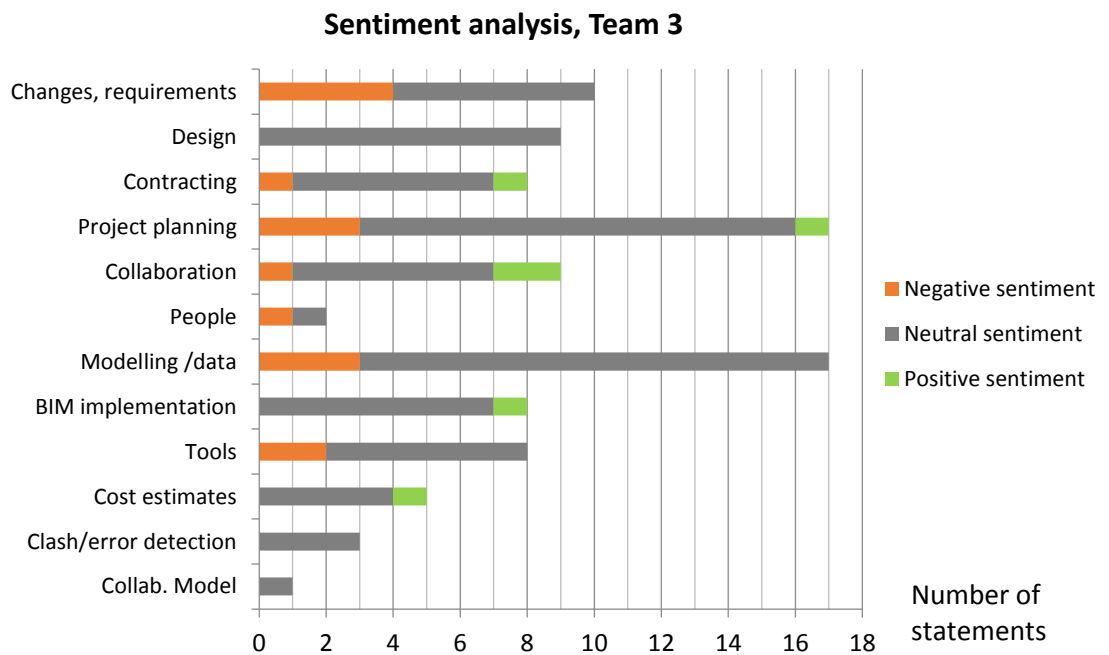


Figure 20: The occurrence of topics and sentiments on workshops: Cases X-Y.

The results of the sentiment analysis of the workshops with Team 3 can be placed both in terms of sentiments and discussed topics between the results of the previous cases. This is partly related to the fact that in both project X and project Y the team was

leading the design process, and thus was able to discuss the design, but could also discuss BIM implementation.

Summary

The discussion of BIM with the team was largely based on the member's general knowledge and past experience, since the Case project Y was in the middle of its realisation at the time the research was conducted. The results of BIM implementation in project Y, therefore, could not be evaluated.

The workshops revealed the differences between the perceptions of benefits of BIM in road and railway projects. As the Team 3 stated, clash detection typically did not play an important role in BIM projects, but the most visible benefit of BIM was cost estimation that allowed evaluating different options during design and provided more accurate estimates. In project X a model for machine control systems was created; another benefit of BIM was possibility to model the space around the track to ensure that the train can go through without colliding with surrounding structures and electricity poles.

The discussion largely repeated the discussions of previous workshops, providing similar findings. The role of the process was discussed extensively, and a number of problems were described related to planning and resources. Besides the fact that designers work at one project at a time and the lack of a master schedule, the team explained how a difficulty to track the design work can affect planning. The role of designers in planning and coordination of work was emphasised.

The Case Y utilised the Last Planner, which addressed the planning problems mentioned above. The team held regular planning sessions on which individual designers communicated their work as broken down in small tasks and provided time estimates for when these tasks are to be completed. The system allowed better mutual understanding of design process, but it was difficult for designers to find out what data they needed to complete the tasks.

4.4.3. General problems in design projects – Team 3

The first problem suggested by the company was lack of communication and knowledge sharing between technical areas. The team members have mentioned this issue multiple times throughout the workshop. The disciplines form knowledge silos, and are focused on their own areas. The problems in communication are enforced by organisational, technical and physical barriers. Lack of communication negatively affects the collaborative work.

- *“Technical areas do not communicate with each other enough*
 - *Interoperability problems*

- *Too many different software*
- *Manual input of information, both related to software and interpersonal communication*
- *Resources change during the project*
- *Inappropriate project organisation*
- *Project members work in different offices*
- *Designers tend to concentrate only on their own areas*
- *There are knowledge silos*
- *Project prioritisation*
- *Line organisation vs. project organisation”*

The second problem that was discussed by Team 3 partly repeated the previous discussion with the Team 2 and related to inability of designers to work only on one project at a time. Most of the suggested causes repeat the problems discussed on the workshops with Team 2.

- *“It is not possible for designers to work only on one project at a time*
 - *No tools for checking the readiness of work of different disciplines*
 - *Lack of cross-checking between different disciplines*
 - *Prioritisation of projects from designers' side (designers, sometimes unconsciously, prioritise projects that are for some reason more attractive to them)*
 - *Timeframes for design are short*
 - *Timeframes for bidding are short*
 - *Urgent issues, communication (e.g. emails, phone calls) disrupt the planned work on a project and force to switch to other project*
 - *Projects that are on different stages (tender, offer calculation, design) occur at the same time.*
 - *There is no master schedule that would put all project schedules together”*

The last problem related to the work content being not clear in the projects and to the changes in work content. This makes designing unclear in the beginning and requires customer to make additional offer. One of the reasons for unclear work content is the lack of information from the previous design stage. That can be related to low quality of initial data, or to missing information. Sometimes an entire design phase can be skipped due to budget or time limitations, and there is not enough information in the beginning of the following phase as a result. Defining the design intent and work content might be also difficult if the stakeholders impose conflicting requirements and have different opinions.

- “Work content is not clear, changes to work content occur
 - Initial data is not available, because it can be e.g. in a wrong format or coordinates; changing requires a lot of time and effort
 - Projects are nowadays faster, design phases are often skipped due to budget limitations
 - There are not enough resources available at the beginning of the projects
 - Not enough initial data of the surroundings, e.g. land use plans
 - Difference of opinions between stakeholders
 - Schedule
 - Customer's budget”

When stating the problems that occur in design projects, the team members mentioned lack of communication and knowledge sharing between disciplines, problems with data management and interoperability. The results of the case study with Team 3 were consistent with other cases and with the concepts identified in the literature review.

5. Discussion and Implications

One of the main goals for the current research was to investigate the current state of the implementation of BIM and possibly other technologies in infrastructure projects in Finland, and to explore the nuances of design practice in infrastructure firms. This was goal was summarised in the third research question:

3. What is the current state of design practice and BIM implementation in the infrastructure sector in Finland? How do the professionals perceive it?

What is special about the research question is that it contains a sub-question and reflects the specific way the research was carried out: (1) through collecting general information about the case projects and (2) through analysing the perception of design team members of both the case projects and the general practices in the companies. Because the majority of data was obtained in interview and workshop format, the perception plays the major role.

The discussion of results in this final chapter starts from answering the research question three, in section 5.1. The purpose of section is to summarise the results of the empirical study that have been presented earlier, and the discussion will be conducted in the following order:

- Design process in the case projects
- Building information modelling in the case projects

After that, the section 5.2 will return to the second research question and suggest how BIM could look like in the future, and what barriers should be overcome to achieve more advanced stages of implementing BIM in infrastructure design projects. The section 5.3 will summarise the findings and discuss some practical implications of this research with regard to what directions companies can take in order to overcome the barriers, and section 5.4 will discuss the methodological limitations of the study and propose some directions for future research.

Finally, the last section (number 5.5) discusses the experience acquired during this research project, in particular the faced difficulties in collecting quantitative data from the case projects. This experience may be valuable for researchers who plan to conduct case studies of design projects in the AEC sector in the future. The section also discusses how software tools and other methods can be implemented to collect quantitative data in infrastructure design projects.

5.1. The current state of infrastructure design in the case projects

5.1.1. Design process in the case projects

Concurrent engineering process

The discussions and project diagrams show that the design process in infrastructure sector is concurrent. The design disciplines work largely in parallel, although commonly the key disciplines start earlier and their work defines to the large extent how the design will look and how much it will cost. In the railway projects, such definitive element of design is track geometry. In road construction the shape of a road, types of intersections and a number of lanes are defined by traffic planning and simulation.

In all case projects the capacity was the main priority for the customer and was a 'fixed' requirement, whereas cost and constructability were variables, aimed to be optimised during design. This could be related to the fact that in infrastructure projects the customer is practically always a public organisation, which possesses substantial resources and can afford certain flexibility in the budget, if spending is justified by the delivered value. However, the fact that the design is 'fixed' already very early in the project is not only related to customer requirements. The design is restricted by the environment: existing infrastructure, surrounding buildings, terrain, ground properties – all have direct and often definitive impact on design and on construction costs.

The order in which the disciplines develop design is generally defined by their level of importance to the project requirements, and the involvement of 'later' disciplines in the early design phases is limited. Design in railway and road projects can be characterised as point-based.

Assessment of design alternatives and cost calculation

In these circumstances, the second task of designers after ensuring constructability, safety and functional requirements, is to minimise construction costs, and to inform the client of design alternatives when such alternatives exist. Minimisation of costs requires cost assessment during the project. According to the project teams, in both BIM and traditional projects costs are calculated for design alternatives when there are such, and the total construction costs are calculated at the end of every design phase. Because cost is not the only factor that has to be taken into account, the selection between design alternatives often requires substantial involvement of the customer.

Cost calculation is performed using specialised software. In traditional projects, this software uses manual data entry, and calculation of costs requires time and effort. Therefore, in traditional design there are limitations regarding cost assessment during projects (e.g. when and how often it can be done). In BIM projects, cost calculations can be done using data obtained directly from the models, which can speed up the calculation process and make calculations more precise, as it has been reported by Team 3. In the future, this can increase the role of cost optimisation in guiding the designs and result in better optimised projects.

Design integration and cross-checking

Fitting the designs together and detection of clashes is a necessary part of collaborative design practice in AEC companies. The traditional process of clash detection has been described in detail by Team 2. Clash detection usually takes place during face-to face meetings between designers from two or more different disciplines, and large team meetings. On the team meetings, designers obtain information about the state of work of other designers, observe each other's designs and coordinate the work. As a designer from Team 2 mentioned, regular meetings help clash detection because designers get information on where to look for clashes. The detection of clashes itself usually happens when designers meet in pairs. These meetings in Case B were very usual and they were easy because designers worked in the same building. Designers combine two CAD drawings to see if they fit each other, and discuss what corrections should be made to designs. Traditional clash detection has limited reliability.

In project A, the detection of clashes was performed by model coordinator or by the team on review meetings, simply by observing the collaboration model. This manual approach has limitations. Firstly, it is also prone to human error and does not allow detection of all clashes. Secondly, it does not allow prioritising the clashes, for example according to their cost. Thirdly, the time needed to observe the collaboration model by model coordinator means that the clash detection cannot be done immediately during design, which implies higher costs for re-design (figure 7, page 22). In the future projects, automatic clash detection can allow faster, more accurate and reliable resolution of clashes during the design process.

Communication

The development of design requires constant coordination effort from involved designers. All case teams have emphasised the importance of face-to-face communication and regular team meetings in design projects.

All the case teams had regular meetings in the projects, with different frequencies. The lack of time can be seen as one of the major barriers to communication: designers usually have to work on design descriptions very intensively in order to meet the schedules, and this is usually done individually. Moreover, designers are occupied with other projects that require meetings too. As a result, there is simply not enough time for meetings.

None of the teams has been entirely satisfied with communication in their work: at least some designers in every team have stated that communication between disciplines was difficult and there could be more communication and more meetings. This was noticed both in the questionnaire and when making the cause-and-effect diagrams of problems in design work. The teams have also made it clear that they see communication as the main facilitator of knowledge sharing, and all teams have mentioned the lack of knowledge sharing or knowledge silos formed by disciplines when asked about problems in their companies. Knowledge silos imply the lack of common language and understanding between technical areas, and the tendency to focus on own narrow scope of problems during projects: *“the technical areas don’t see what others are doing and do not discuss with each other”*.

Design planning and control

Project management was one of the most discussed topics on the workshops. The case project teams reported difficulties related to project planning and control. Particularly, the general planning and management practice in infrastructure design firms was discussed with the teams 2 and 3. Team 3 provided especially valuable information about control and scheduling in projects and about the team’s experience of using Last Planner.

The first project management problem to be described here is related to the lack of visibility of design work in projects. As it was mentioned earlier, designers have to see each other’s work and conduct face-to-face discussions in order to eliminate inconsistencies, coordinate the work and to obtain shared understanding of design. Project managers need to know how far every designer is, if there are any potential problems or risks for the project and if any actions need to be taken.

The visibility problem results from the fact that design information is not available in real time as design evolves, and is delivered occasionally by designers, usually when their tasks are complete or close to completion. As a result, a project manager and the rest of the team can see the work of every designer only after a rather complete version

of this design has been shared. Between the start of the task and the delivery of design it is hard for others to know how far the work has progressed, which makes coordination difficult.

Designers have their individual virtual environment in which they carry out their tasks. They share information with certain regularity, and prefer to share design descriptions when they are 'ready enough'. Sometimes, they even tend to 'hide' their work on personal computers, so that unfinished work is not seen by others. On one hand, this can potentially reduce the risk of making other designers rework in case something changes later in the shared designs. On the other hand, late delivery of data can cause unnecessary waiting and will surely make design process less visible to others. Team 2 emphasised that sharing the day's work on a project drive was considered a good practice and was mandatory for all team members.

One could imagine that, even if there is no constant possibility to see the work of designers in progress, it is still possible to estimate how much of the work have been completed based on comparison between time reserved for the design tasks and time spent by designers. In Case A, the project manager was able to notice that one of the designers did excessive work when the amount of hours spent by this designer started to exceed the plan. This means that the project manager was not able to know about this problem before it visibly affected the project costs. Team 3 have mentioned that *"For the project manager, the only way (to know about the progress) is to look at the spent hours. So if the half of the time budget is spent, he can only assume and hope that half of the work is done."*

Therefore, *the second problem* relates to controlling the resources in projects: how much time is being spent on every task. In addition to the lack of visibility, it is hard to plan how much resources have to be spent and to control it because the outcome is intangible and the work cannot be calculated in the same way as in manufacturing activities. Therefore, in design projects it is generally difficult to relate the resources (time) to the outcomes. This is a conceptual problem that can be seen in other service activities.

As the case teams explained, it is almost a rule that designers in engineering firms work on several projects at a time. A traditional project schedule shows the dates when tasks start and the dates when they should be finished, but the schedule does not show the workload of designers, or how much time a designer spends on each task. Designers can spend 4 hours a week on a project or 4 days a week, and this is never reflected in the project schedules (figure 21).

The case companies do not employ company-wide schedules that could integrate schedules of all their projects, which makes the division of designers' time and effort between projects uncontrollable, and to some extent up to designers' wish.

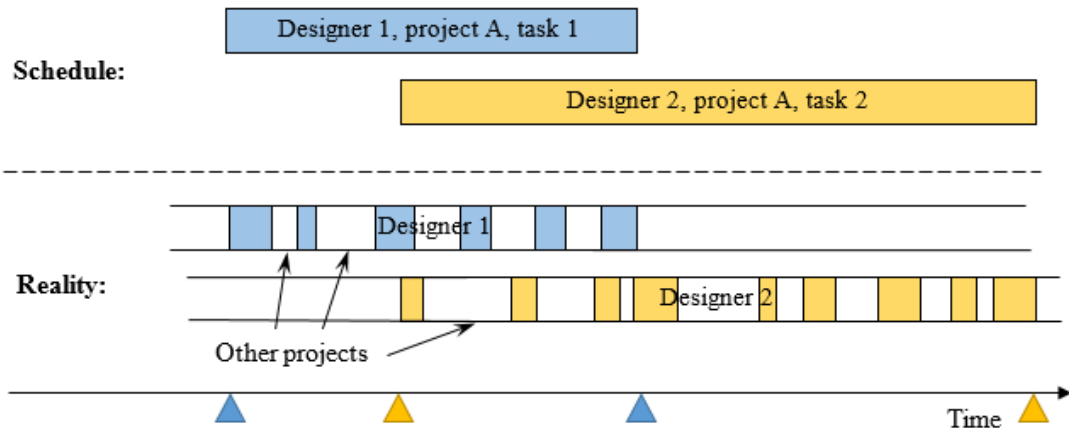


Figure 21: The design tasks as shown in project schedules; the schedule (on top) is an estimate and does not reflect the actual amount of hours spent on a project.

According to Team 3, sometimes designers start paying more attention to one project unconsciously and spend more time on it than on other projects, even if this is not required. Such ‘prioritisation’ may be caused by creative interest of a designer or his own understanding of which project is more important. This can have an adverse effect on other projects.

As Team 3 has mentioned, the ability to control the projects could be increased if design tasks were split into smaller fragments and reflected in schedule in a detailed way, and if, as a consequence, design data was delivered more frequently in smaller batches. This would help designers follow each other’s work more frequently.

Team 3 in Case Y utilised the Last Planner system of production control. The Last Planner (Ballard, 2000) is a method of planning and control that is based on continuous planning throughout the project, direct involvement of designers in planning, division of large tasks into small sub-tasks with clear connections between them, and regular meetings. The results of implementation of Last Planner in the case project were positive, although, according to the project manager, designers had difficulties figuring out what they need from each other in order to complete their own tasks. The method required designers to change their way of thinking and to learn better how their work is connected to the work of other team members.

Case Y was an exception: in the rest of the case projects no clear methodology for planning was implemented whatsoever; the designers had limited involvement in planning and at most provided time estimates in the beginning of projects. Coordination and control during the projects, except for project Y, were rather ad-hoc and the schedules were not detailed, showing only standard high-level tasks that would typically occupy several months on a timescale. Besides the time component of planning, the content of work was also not very well defined, according to Team 2, which sometimes led to changes, additional orders and delays. The schedules were

often made only before or at the beginning of the projects and were not updated later although changes occurred.

Team 2, which was involved in Case B, has stated that the industry does not appreciate planning as it probably should, and planning is too basic and high-level. The designers from all the project teams have said that the main reason for the lack of planning in projects is the time and budget constraints: designers cannot spend too many hours on planning and too many people cannot be involved in the beginning of the projects, otherwise the costs would grow. Team 2 has suggested that employing project management software could be beneficial to aid managers. The team's statement that there were no tools, in general, could either mean that the companies were unfamiliar with the available tools or that there were no tools that could meet the needs of design projects in infrastructure construction.

Information management

The main information exchanges that occur in projects are deliveries of design data and meetings between project members. After examining the project swimlane diagrams and the other data, it has been noticed that meetings, deliveries of data and start/completion of tasks often occur at the same time, which points at the relations between tasks and allows attributing information exchange events (data deliveries, meetings) to the tasks. Since many tasks require long time to be accomplished, the frequency of information exchanges is not very high in projects. The mutual awareness of design is generally established on team meetings.

There were also minor problems related to tracking actions and realising what files carried the newest information. For example, shared project drives do not allow seeing this information in file metadata. As an option, designer might reflect this information in file names, although it is not done in every project. Some specialised data management solutions (e.g. project banks) can track updates and other operations with files automatically, and record all relevant information in file metadata.

Although in the case projects such solutions were used they were only meant for the final designs, and internal exchange of design data was done via shared project folders and even emails. The email was mentioned to be the least efficient channel because of the limited file size and long waiting times for uploading and downloading, and, most importantly, because only the recipient of an email could see the file and not the rest of the team.

In addition, occasional working with incomplete data, as a consequence of parallelism of design tasks, has been mentioned as one of the problems by Team 2. This problem was found in the literature, for example, in the article by Eppinger (2001).

Summary: process view on design practice in infrastructure projects

The study have not revealed significant differences between the traditional and the BIM projects in the way projects were managed and work was organised. The differences concerned primarily the technical aspects of designing. The design process was characterised by a range of problems which have also been reported in the literature and which were similar in conventional and BIM projects. The findings have confirmed the notions found in the literature with regard to the problems of collaborative design, and have also shown high awareness of the project teams concerning the problems of their work process.

The list below is a summary of characteristics of projects that were suggested by designers as current problems (the original lists can be found in each third subsection of sections 4.2 – 4.4):

- Lack of communication
- Lack of information sharing
- Lack of tools for data management
- Insufficient data from previous phases
- Unclear scope of work
- Tight schedules, lack of time
- Designers work with many projects at the same time
- Project organisation grows too large
- Basic and inaccurate planning
- Lack of tools for project management
- Designers use different formats
- Lack of cross-checking between disciplines
- Long finishing phase of design projects

In general, the ad-hoc project planning, lack of work control and coordination were the most discussed topics related to design. The lack of proper information management was also a much discussed problem. BIM and other technologies and methods (project bank solutions, project scheduling and control software, Last Planner and possibly Big Room) can be used to reduce the impact of some of the discovered problems, for instance, the low visibility of design outside the discipline creating it.

Generally, the need for process improvement is recognised by companies but the resources are scarce to reengineer the processes and designers are used to old practices, which makes any change difficult. How this affects the implementation of BIM and what the potential of BIM to improve the design is will be discussed in the following sections.

5.1.2. Building Information Modelling in the case projects

Perception of Building Information Modelling by the case teams

When the members of the design teams were asked to state the characteristics of BIM that they knew in an open-ended question, the team members have stated a variety of benefits, most of which are also found in the reviewed literature. The suggested benefits are presented on figure 22, and have been shown in more detail on figure 16, section 4.1., page 42. Among the benefits suggested by the researchers in questionnaire and in discussion, the most prominent were: (1) *design data integration and clash detection*, and (2) *cost calculation and evaluation of design alternatives*.

As Team 3 reported, cost estimation was done with better precision with the help of BIM. Cost estimation was seen by the company as one of the primary benefits of BIM in railway projects. In the Case A, which was a road design project, the manager viewed model-based cost estimation during design as one of the potential benefits of BIM, although in the case itself cost estimation was done in a traditional way. However, according to the case team, BIM was used for decision making on the initial design stage primary to the project A, for evaluating various design alternatives with the customer. In both BIM cases the models were used to present the designs to the client and public.

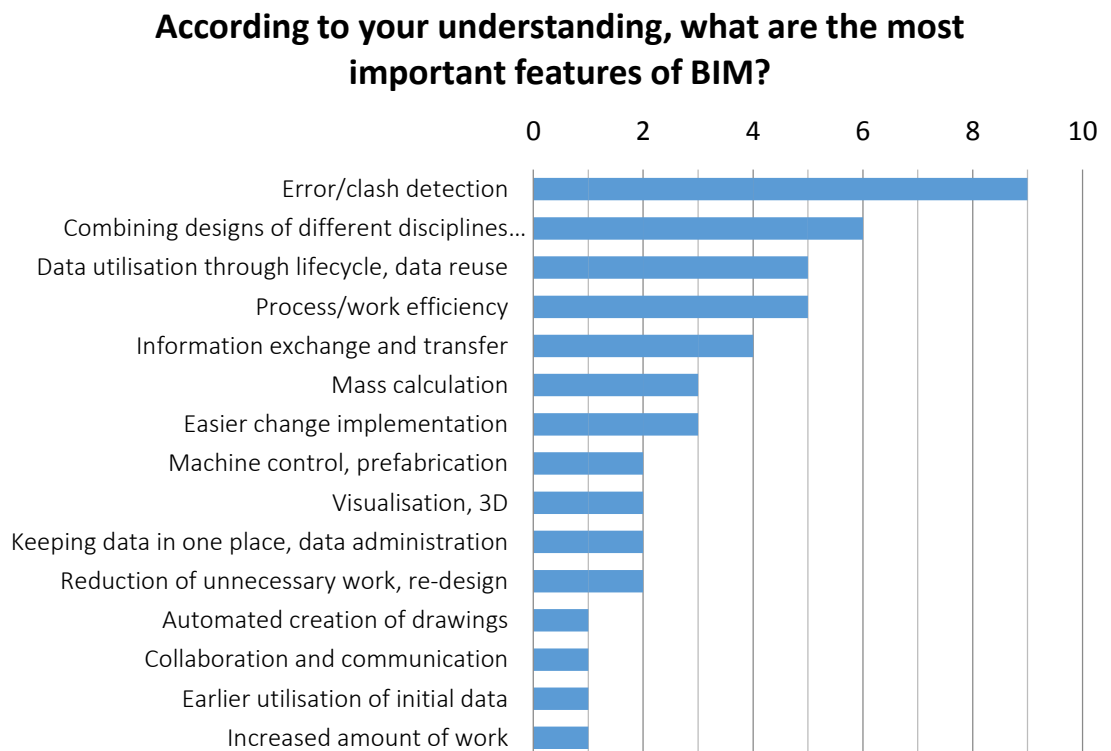


Figure 22: Open-ended question about the features of BIM – answers categorised and arranged in a stacked bar chart.

The role of collaboration model for clash detection was especially important in Case A, which was a road project. In this case it allowed detection of two clashes that would not have been recognised otherwise and that constituted a substantial risk for construction. Team 1 stated that, according to their client, *the possible savings from detecting these clashes alone covered the whole cost of BIM project*. Team 3, which was involved in railway projects, stated that clash detection was important in particular cases, but it was not as important benefit for railway design as, for example, cost estimation. Overall, clash detection was the most recognised benefit of BIM among the participants of the research, according to the questionnaire study.

In spite of the benefits, it is unclear how BIM-based clash detection affected the design integration in the Case project A compared to traditional projects: whether it was performed in addition to traditional clash detection process, or whether it to any extent replaced the traditional process, making the designers rely more on the instructions of model coordinator than on peer-to-peer meetings. If the latter was the case, it could have had an adverse effect on communication by decreasing the information exchange between disciplines. The measurement of impact of BIM in its current state of implementation on communication in projects requires in-depth analysis that is beyond the possibilities of this research, but it is an interesting topic for future studies.

In addition to implementing BIM in projects A and Y, digital models for machine control systems were made in project X after design was finished. With regard to other benefits suggested by designers, there is less strong evidence that they were realised in the case projects, since most of them are very intangible.

The way how Building Information Modelling was perceived by the case teams is characterised by a contradiction. In the questionnaire, the benefits of BIM were rated differently, depending on how questions were formulated: whether designers were asked about the general properties of BIM or about their experience of BIM in projects.

For example, the parametric object-based modelling can make some routine design tasks easier to perform (Eastman et al., 2008: 14), and this can explain why such benefits as work efficiency and easier change implementation were suggested by designers (see figure 22). However, when asked to rate a pre-defined set of impacts of BIM on the actual projects, the designers have given negative ratings to several process-related characteristics: the impact of BIM on project delivery time, time required for changes and additions and ease and joy of working (although the latter caused controversy among respondents). The fact that these characteristics were rated negatively directly contradicts the responses shown in figure 22.

The actual impact of BIM on parameters related to information exchange and management is also unclear. Although designers have stated that the impact of BIM is positive, the overview of current design process suggests that the information

exchange in BIM projects is identical to such in traditional projects. The fact that model integration and a major share of modelling were performed as a separate process by BIM experts, suggests that the information flow in BIM projects could be somewhat more complicated than in conventional projects, especially since all traditional documentation in such projects is still delivered to the customer.

When asked to rate the level of satisfaction with the process of working with BIM, designers, who have previously been involved in BIM projects, gave very low ratings relative to the scale: 4,5 out of 7 by experienced BIM users and 2,75 out of 7 by less experienced users (see figure 13 on page 39, section 4.1). On the other hand, when asked about the willingness to work with BIM in future, the designers gave high grades: 6,83 by experienced users and 5,75 by less experienced ones, on the scale of 7 (see figure 12 on page 39, section 4.1).

During the workshops, the members of BIM projects were especially critical of many process-related aspects of implementing BIM. The low quality of models provided by third parties and by designers in the teams, the difficulties in exchanging information and in communicating instructions to designers, the lack of standards and guidelines – all these problems were mentioned very often. The critical attitude towards the process is especially evident from the sentiment analysis charts presented in sections 4.2-4.4. Some professionals on the workshops, while acknowledging the benefits of BIM for the owners and construction phase, referred to it as ‘additional work’ on design phase.

These results have two important implications. The first one is that the problems that occur when implementing BIM are largely related to process, as it has been initially thought when planning this research. This means that the potential of BIM is not realised to the full extent and the barriers to it should be overcome by industry.

The second implication that results from the controversies in the responses is that there is a difference between how designers perceive the potential benefits of BIM (what BIM is supposed to give to designers) and how they perceive the actual design and modelling process in their companies (what BIM actually gives to them).

Although BIM already provides significant benefits, such as 3-D visualisation of designs, timely detection of errors and clashes and the ability to choose the best alternative using automatic cost estimates, these quality-related benefits are not visible for the individual designers working in projects, since many of them materialise only during or after the construction phase. The use of BIM was still mostly the initiative of project owners, although the case companies also valued the experience they acquired during the projects, and recognised this experience as their competitive advantage. As the project manager of Team 3 has mentioned in the interview, *“all the new things can have a negative effect, but we (the case company) understand that this*

(BIM) is future, you can't do the design always in a traditional way. If you want to do design in future, you have to learn BIM."

The merit of calculating ROI of BIM implementation in design projects.

None of the case projects attempted to measure the return of investment in BIM implementation or the economic effect of any of the benefits of BIM in particular. As described in the beginning of this study, conducting such measurement in the context of intangible project-based activity is a very hard task. In addition, the companies do not have resources, especially time, to conduct extensive studies. For design companies, the only indication of whether BIM is beneficial or not is the possible additional profit in a BIM project. It is difficult to attribute a particular difference in design costs between projects to the fact that BIM was used in one of them, and separate this from other factors, or to measure the improvement in design quality.

The discussions with the teams and the study of perception suggest that the companies rely on their vision of the future when developing and implementing a new technology. Measuring the benefits of BIM is not only difficult because of the lack of instruments and resources for data collection. With regard to the design phase of infrastructure projects, it is difficult because there may not be many benefits for designers on the current level of development of BIM at all, although there are benefits for the construction phase. Nevertheless, the additional revenue received by design firms in BIM projects can outweigh the possible costs of additional work. Finally, a set of innovative technologies and approaches like BIM is not a product of a laboratory – the only way it can be developed is through years of application in industry.

Even the professionals cannot say exactly in what direction and how far the technology develops in several years. The fact that managers cannot calculate exactly how much money the technology will return does not prevent more and more companies to join the BIM race, even though the technology could be not very rewarding for them in a short term. The likely motivator for companies is not only their perception of current and future benefits or the willingness of their clients, but also the pressure from competitors, who may “get there first”.

It can be concluded that the need for quantitative studies of benefits of BIM for design at this level of development is partially overestimated. However, there is a certain risk that the industry may stop the investment in technology if the benefits are not proven with time. The measurement in design phase is needed as a part of development of BIM, in order to benchmark the different ways of implementing BIM in design projects and find the best practices.

The deficiencies in the current state of BIM process

BIM, as it was implemented in the case projects, gave little benefits to collaboration, as in neither of the two projects that utilised BIM could the designers use the collaboration models.

According to the description of modelling process by the project A team (presented in subsection 4.2.2), there was a substantial disconnection between design and modelling in the project. One of the reasons for that was that the designing was already taken to detailed level on the previous design phase: most of the alternatives have been already evaluated and selected. Therefore, the primary function of BIM in the project was clash detection.

The model coordinator was responsible for the integration of all design data. The data provided by designers in most cases needed some modification before it could be included in the collaboration model, and this modification required manual inputs. The swimlane diagram of the project created together with the team shows that this integration and correction process took around three months.

The correction and completion phase can be viewed as a bottleneck in the project workflow, at least in Case A. The process relied mostly on model coordinator, and, according to largely negative sentiments on the workshops, could place excessive burden on him and other BIM experts. Model integration in the project was done at the later phase of designing; there was a substantial time lag between receiving the designs and addition of data to collaboration model.

This type of BIM process is illustrated on Figure 23, a diagram based on the swimlane diagrams of the case projects created during the study. The figure shows that the process of correction and completion in BIM projects is performed as a cycle, and starts at a late phase of a project after most of solutions are ready. The diagram also shows data exchange practices and tools.

In the Case Y, the collaboration model was not created by the time of the workshop, five months since the start of the project, which suggests that the characteristics of BIM process were not much different from project A.

The deficiencies of the current BIM process, the various problems that occur when implementing BIM, and the lack of visible benefits for designers can become objective reasons for designers' resistance to the technology, even though the impact of the lack of knowledge and natural resistance to change should not be discarded. As the questionnaire has shown, the designers have negatively rated the impact of BIM on project duration, duration of tasks and ease and joy of working. Moreover, the number of negative statements is higher among the designers who have worked in just one or

two BIM projects. This shows that there is some resistance to new technology and lack of knowledge of benefits among designers with little BIM experience.

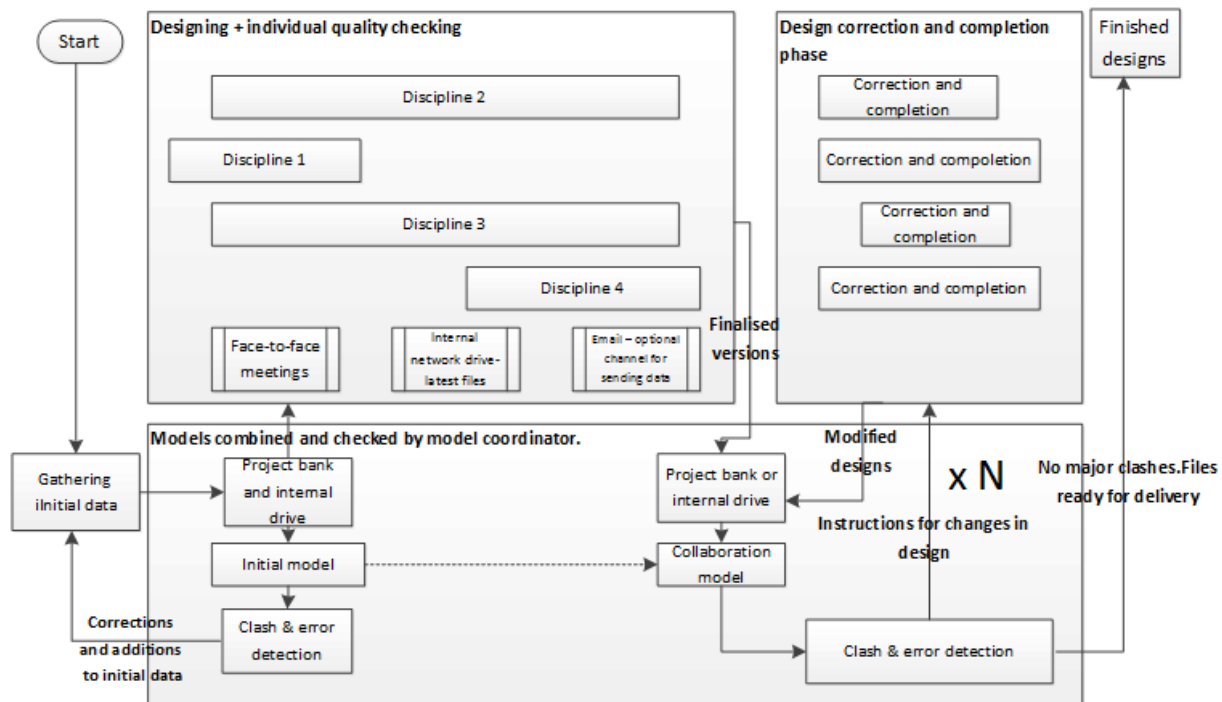


Figure 23: BIM process in the case projects, stage 1 of BIM implementation.

The results of the questionnaire show that novel users who experienced only 1-2 of BIM projects have less precise understanding of the benefits and objectives of BIM compared to BIM experts. Novices tend to notice the somewhat negative impact of BIM on their work more than the experts do, since they naturally have difficulties learning and adapting to new methods of work. Finally, novices have less satisfaction in BIM projects.

The absence of BIM users with experience of 3 to 6 projects can suggest that the transition of designers from novice to expert level with regard to BIM knowledge is currently unachieved. The low number of BIM projects and the temporary nature of project teams can be a barrier for systematic increase in BIM experience among the BIM users.

The fact that the teams break apart and the knowledge flow disrupts after each project has a negative impact on knowledge dissemination, and this problem is typical for project-based business (Gann and Salter, 1998). The problem can have a major impact on implementation of BIM. If a designer is taken to one BIM project only and does not continue working in projects that use BIM afterwards, he is not likely to receive the amount of skills and knowledge that could give the actual advantage to his company. The significant gap between the BIM experts and new BIM users, which

manifested itself in the questionnaire, might point out at areas where knowledge management could be improved in companies.

Team 1 has expressed their dissatisfaction with designers' response to BIM particularly often during the workshops. The BIM experts agreed that the common designers in the project followed instructions at most. There were problems with both the designers' attitude and the quality of supplied models. Taking that into account, it can be stated that the gap between new BIM users and BIM experts reflects the gap between BIM process and designing that is depicted on figure 23.

The overall state of BIM implementation in the case projects could be placed between stage 1 (object-based modelling) and stage 2 (model-based collaboration) of Succar's BIM maturity model (2009). The case companies employed various modelling tools within several disciplines, and there was transition of models between different companies and project phases. However, such transition was largely jeopardised by the lack of software interoperability and various problems with model quality, as in Case A. Complementary data transfers and manual modifications to the models were needed in many cases, both in data transfer within companies and between different project parties. Therefore, although the state of BIM in the case projects was somewhat beyond just object-based modelling, it still could not meet the criteria of model-based collaboration.

Summary: the level of BIM maturity and identified problems

The level of implementation of BIM in the case companies is mostly consistent with the first stage of Succar's BIM maturity model (2009), and only some parameters as utilisation of BIM between design phases qualify for the second stage. The current BIM process in one design phase and one company, as depicted on figure 20, will be considered in this research a first stage of BIM implementation in a design company. On this stage, BIM does not have any major effect on collaboration and information exchange; the designers do not use the collaboration model.

The correction and completion phase of the project is affected by BIM on this stage, since clash and error detection is used to identify and correct errors in design. This process may add extra design iterations and require additional time at the end of the project, but this is beneficial for the quality of design and reduces the clashes. In addition, the use of model-based cost estimation results in faster and more precise estimates. The value of utilising BIM in the projects is actualised mainly by savings of construction costs for the owner. On the current level of implementation of BIM, the designers cannot sense the benefits of the process.

Here are the list of problems related to implementation of BIM that were formulated by the Case A and Y teams:

- *Collaboration model is under-used*

- *Faulty initial data*
- *Lack of quality checking*
- *Lack of process guidelines*
- *Interoperability problems*
- *Too many different software products*
- *Manual input of information is required*
- *Lack of software skills*
- *Designers use different formats/templates*
- *Updates to designs not timely enough*
- *Old habits and change resistance*
- *Design and modelling is separate*

The major problem identified in the case projects is the low quality of received and created design data, which includes the initial data, the designs created internally and the data received from third parties. The quality of data does not meet the standards necessary for seamless model integration, and most often requires some intervention from the model coordinator (integrator). The quality problem results from the lack of modelling skills among the participants, the lack of proper internal quality checking and the lack of guidelines for modelling and quality checking.

The fact that the process quality does not satisfy the teams can contribute to the decrease in motivation and the resistance to change among designers with regard to BIM implementation. Some of the results indicate that there is no systematic organisational learning policy in place to allow employees sustainably achieve high levels of BIM expertise. In addition to the process-related problems, the companies lack the knowledge of available BIM tools and the expertise in using them; they also lack the expertise of creating the proper software and network infrastructure for the projects that would allow interoperability and fast exchange of information. There could as well be shortcomings in the software tools, especially in the older case projects.

5.2. Towards BIM-based collaborative design in construction

This section returns to the potential role of technology in infrastructure design practice, which was previously discussed in the literature review chapter. The section mainly discusses the achievement of collaborative BIM process, which was not in place in the case projects. The section proposes some additional answers to the research question 2, now taking the results of the empirical study into account:

2. What is the potential role of BIM and other technologies in maximising the efficiency and effectiveness of collaborative design in construction projects?

5.2.1. BIM as a tool for collaborative design

The traditional design process reminds of a painting workshop in which a number of artists work on one painting. The difficulty is that the specialised artists have to work in different rooms on their own fragments without the possibility to see the whole painting. Their fragments, however, should perfectly fit each other, and therefore the artists have to meet regularly to discuss and exchange their work. The artists should also be very fast and efficient in order to finish every painting in time, although they have many paintings that they are simultaneously working on, sometimes switching from one to another few times a day. This absurd example may illustrate where the problems of collaborative engineering in such industries as construction stem from.

Building information modelling can make it possible for building and infrastructure designers to see both their own part and the whole design when doing their work. BIM could resolve the issue of design visibility by providing a shared virtual 3D environment, in which all designs will be integrated from the very beginning of the project, ideally – in real time.

In BIM projects, designers can work in 2D or 3D on their own fragment of the work and these discipline-specific models have to be integrated into a collaboration model. In the case projects, as shown on the process model on figure 20, this integration process was carried out at the later phase, mainly by the model coordinator (therefore this role is also often called ‘model integrator’). The purpose of BIM, as it has been already discussed, was to detect clashes in all projects and estimate the project costs in the railway project; the models were also seen to have value for the customer as such. The value of BIM implementation, therefore, is likely to actualise mainly on the construction stage of the projects. The collaboration model was not used by designers.

Realisation of benefits of BIM during design and for design requires substantial change in the design companies’ understanding of the goals of BIM and its role in the design process. A number of articles reviewed during this research explore the benefits of BIM server technology and IFC-based data exchange for design collaboration. These studies emphasise the potential role of BIM in future projects as design data repository, which can largely replace the conventional data exchange process and serve as a multi-disciplinary collaboration platform. (Singh, Gu and Wang, 2011; Poerschke et al., 2010; Plume and Mitchell, 2007)

One of the experiments when such BIM-based collaboration was achieved is described the study conducted by Poerschke et al. (2010). In the research, the university students of three architecture and engineering departments of 3rd to 5th year of studies worked in a collaborative studio that utilised BIM server technology. The students used BIM for data collection, analysis, design development, data coordination and project presentations.

As the study reports, “*Students from different disciplines could draw upon **one central model**, redefine it for their own needs, perform complex analyses in **discipline-specific software using separate models**, and then **re-inform the central model** (with some hurdles of information backflow to the model). In contrast, a studio that embraces just one discipline seems limited in exploring the collaboration potentials of BIM.*” However, the difficulties faced in using the collaboration model during the experiment included interoperability problems, data administration, lack of BIM skills and education, and a need for detailed workflow planning, which is similar to the results of the current research. (Poerschke et al., 2010)

The potential benefits of using BIM as a cross-disciplinary collaboration platform are especially important in the light of the problems of traditional design process in the AEC sector found in the literature and revealed in the empirical part of this study (see subsection 5.1.1). Firstly, the use of BIM collaboration servers and the project data handling solutions (project banks) can resolve such problems as versioning and availability of data. Secondly, the problems related to project-management and workflow planning, such as undetailed scheduling and difficulty to see the progress of work in individual disciplines, are likely to be resolved with the use of collaborative BIM. What is particularly important is the interrelation between the use of BIM as a collaboration platform and the reduction of batch (increment) size in the design process, since the collaborative BIM requires more frequent sharing of design data.

As discussed earlier, the division of general tasks into smaller sub-tasks and therefore the more detailed reflection of design process in schedules, possibly using the Last Planner system, can benefit project management. The more frequent delivery of design data can help collaboration by enabling early cross-checking and analysis of designs. As the reviewed literature suggests, smaller and more frequent design iterations or increments can also reduce the waste related to design changes, similarly to the concept of Agile (section 2.4). At the same time, the frequent uploads of design data to collaboration model starting from the earliest weeks of design project, and the opportunity for designers to use collaboration model, are the main characteristics that make the difference between the current process identified in the case projects and the collaborative BIM process.

The next step in developing the BIM process is illustrated on Figure 24. The illustration shows differences from the current process depicted earlier on Figure 23 (subsection 5.1.2). There is no division between the design phase and the integration/correction phase any more: the additions to collaboration models and model revisions are done frequently throughout the project.

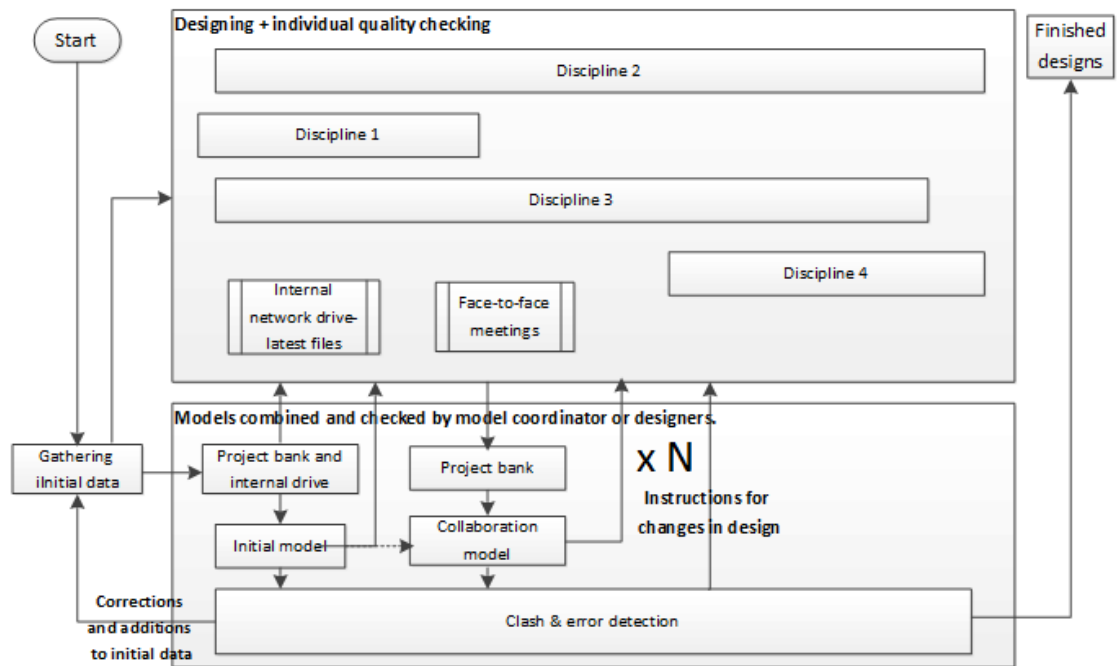


Figure 24: Potential stage 2 of BIM implementation: revisions are done frequently during design, BIM is used as a collaboration platform.

The letter N on the diagram represents the number of increments made to the collaboration model; the number of increments should be reasonably high and should be chosen based on how much time is required to integrate the discipline-specific design data. When the process, skills and technology improve, this number is possible to increase.

Possibly, the future technology would allow saving designs directly to a network-based collaboration model and would not require any model integration and updates at all. On this level designers would be able to see both their discipline-specific data and the collaboration model in real time while their work proceeds. This possible future BIM process is depicted on figure 25.

The process models depicted above are related to the capability stages of Succar's BIM maturity model (2009). The Succar's capability stages describe the steps towards collaborative BIM process in the whole project between different stages of life cycle and/or companies, but also mention the level of BIM-based collaboration between different disciplines which can also take place within one company. The models proposed in this work describe the level of maturity of BIM mainly within one company and one design phase. Nevertheless, the process models above illustrate the similar idea as the Succar's work. In both models the level of collaboration is dependent on the technology, for example, the advanced network-based (server) technology is also mentioned in Succar's model as a pre-requisite of achieving the Stage 3 of BIM capability.

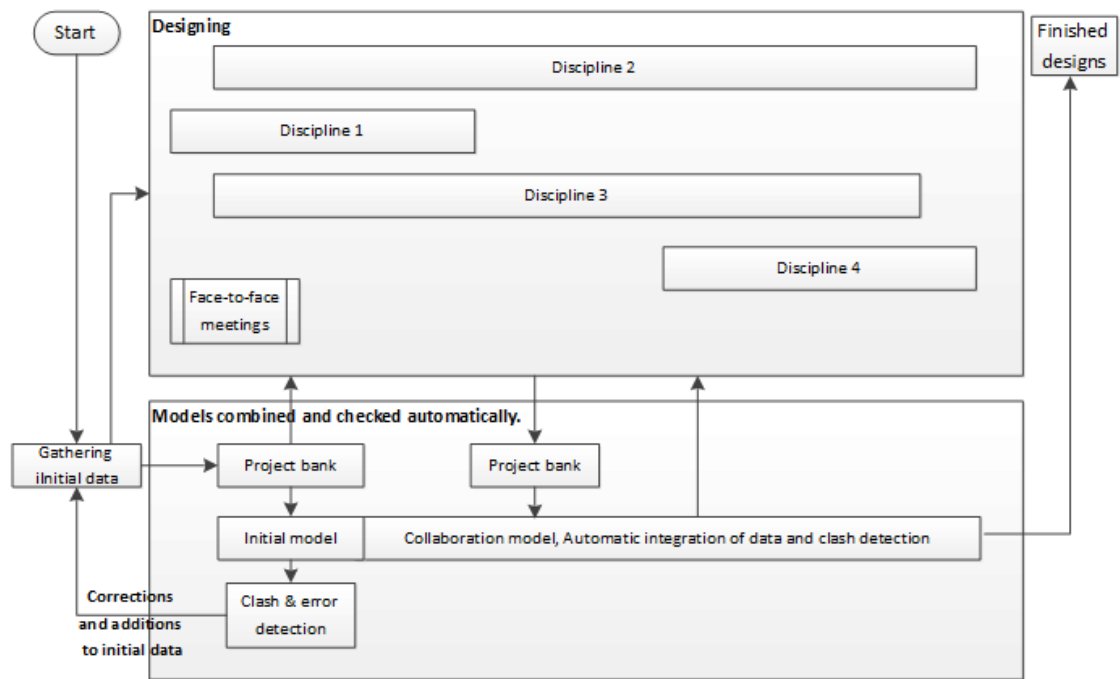


Figure 25: Potential stage 3 of BIM implementation: shared virtual design environment, automatic integration of design data and clash detection.

5.2.2. Barriers for achieving BIM-based collaboration in design projects

The existing time gap between designing and the integration of discipline-specific data in a collaboration model makes the model not very usable for designers. To make the model useful for them, the integration lead-time should be as short as possible, and the fragments of design should be integrated starting from the beginning of projects, so that the team can see and use the collaboration model right after they create new design data.

The additions to collaboration model should be made more frequently (figure 24), and in the best case – immediately after new data is delivered (figure 25). This will also allow performing clash detection and cost estimation earlier. Since the cost of re-designing increases when design proceeds (figure 7, section 2.4), making clash detection as early as possible will contribute to the decrease in rework needed to fix the clashes.

According to the case data, the integration of models is the key technical barrier in projects to achieving this stage of integration of BIM into the design process. On this level of technology, process and skills, the individual discipline-specific designs cannot be taken to collaboration model so easily. As the designers from Team 3 have said, “*Ideally, we should design by modelling*”; but this is not achieved currently.

As the Case A have shown, there were substantial problems with the quality of data provided by third parties, including the initial data, and with the data provided by some designers within the project team. The model coordinator had either to fix most of the models when the required corrections were less substantial, or send the models back to designers. This cycle of correction has repeated several times. The difficulty to transfer design data to collaboration model can be explained by the following problems, which have all been mentioned on the workshops:

1. Traditional 2D-based designing is still used by some disciplines, and in those cases modelling has to be done separately by a BIM specialist after the design.
2. Low IT skills of designers, little or no experience of working with BIM.
3. Lack of modelling guidelines, standards and formats (e.g. designers use ambiguous coordinate systems).
4. Lack of quality checking procedures for data prior to submission, both for designers and for third parties.
5. Poor software interoperability, although this has been significantly improved in the recent years according to the case teams.
6. Suitable software is lacking or not used for some of the disciplines and applications. For instance, in the project A the bridge designer has reported difficulties because there was no modelling software completely suitable for complex bridge geometry. In the same project, the poor quality of models made by the third party was assumed to be caused by the use of unsuitable software.
7. Required IT infrastructure is lacking in some companies for the use of shared collaboration models. For instance, in Case Y no suitable technical solution for collaboration model server have been found by the middle of the project.
8. Outdated BIM tools: in some older software 3D models are displayed in a separate program and it is technically impossible to observe 3D views while designing; in the newest software this has been improved.
9. Difficult navigation in 3D models, especially for unexperienced designers.

While the technology-related barriers cannot be overcome by designers and are the primary concern of software developers, the design companies can improve their BIM skills and processes. In the advanced BIM process of today it should already be possible to reduce the modelling lead-times and achieve regular model integration at least for the major disciplines.

5.3. Summary and practical recommendations

In this section the implications of the findings for design companies are discussed. Possible directions for future research are proposed, taking into account the experience obtained when conducting the study. The section aims at answering the last of the four

research questions, not definitively but through argumentation and suggestion because the proposals have not been practically tested in this study:

RQ4. What actions can be taken by the design companies in infrastructure sector regarding the technological and process development in order to increase performance in design activities?

The currently achieved first stage of BIM implementation, which has been described in detail in subsection 5.2.1, means that the potential of BIM to serve as a tool for collaborative design and improve the design process is not realised. In the case projects, none of the designers used the collaboration models and the creation of collaboration models by model coordinators was done or was planned to be done at the projects' later phase.

The detailed study of case project A has provided evidence that the way the modelling process is organised in the case project can extend its completion phase. The responsibility of a model coordinator is to control and improve the quality of data provided by specialty designers and to provide them with instructions for correcting the designs. This lengthy process can possibly slow down the work at the later stage of a project, making model integration and correction a bottleneck.

Such benefits of BIM as clash detection and cost estimation, however, have a decisive impact on projects through improving the design quality. This impact is realised mostly by the customer, for instance, in the Case Project A the client has reported major savings from clash detection. The companies are currently moving towards a higher level of integration of BIM in the design process.

The barriers towards achieving collaborative BIM include the different factors that force designers to use traditional methods and make the integration of designs into a collaborative model difficult. The large share of designs is still done in 2D and the quality of provided data undermines the ability to integrate it. There is generally a lack of process guidelines and standards for modelling and exchange of information, although the degree of similarity between projects of one type in infrastructure sector (e.g. road projects, railway projects) provides the possibility for standardisation in the future with adjustments for the needs of disciplines, similarly to the way traditional design was standardised in the sector.

The capability of design companies to implement BIM more effectively depends largely on the skills and attitudes of employees. The questionnaire study revealed a gap between common designers, who are in most cases novel users of BIM, and BIM experts. This gap manifests itself in differing levels of knowledge in BIM-related topics and differing attitudes to BIM and its impact on work process. The attitudes of novel users tend to be more negative. At the same time, the study shows no respondents

who would be in transition between a novel user and an expert: there were no respondents in the case teams with the experience of 3-6 BIM projects, and the only identified groups were novel users (1-2 projects) and BIM experts (>7 projects).

Such obvious division in the levels of experience may be an indication of a disruption in learning. Designers from both companies have mentioned that teams in their companies were usually temporary. Even if the management team stays unchanged from project to project, a large part of design team is different every time. This means that there is a high chance that a designer participates only in one BIM project and after that does not participate in any BIM projects for a long time. It is likely then that a company will get many of its designers to participate in one project that uses BIM, but that practice is not beneficial because one project does not give a designer the level of knowledge and skill that could make a difference for the company.

This claim is supported by the results of the questionnaire study and the opinions of BIM experts. Disruption in the learning process at the end of a project is typical for project-based firms in general (Gann and Salter, 1998). Unchanging BIM teams, systematic mentoring practices and emphasis on knowledge exchange have a potential to enable the transition of employees from novice level to BIM expert level and can also improve the way designers work together in teams.

The study of design process in general have revealed several areas where improvement can result in leaner, more efficient designing, regardless of whether BIM is used or not. While the previously mentioned areas of improvement relate to overcoming the barriers to collaborative BIM, the following areas relate directly to the problems of designing (figure 26). The detailed description of these problems have been presented earlier in subsection 5.1.1.

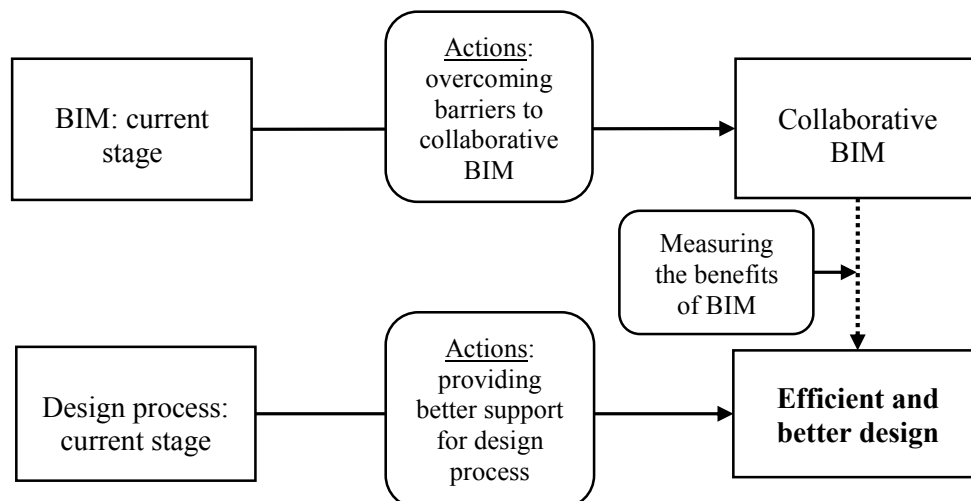


Figure 26: Focus areas for design companies in infrastructure sector

The first area is information management: the project teams have reported some difficulties regarding the management of design data, management of updates, tracking of actions with files and data availability. When the necessary data is unavailable for a user it can result in a delay or force this designer to work with incomplete data. A designer can also work with outdated or incorrect data. The suggestions of the project teams have fallen into categories of problems proposed by the reviewed articles on lean information management. The problems can be addressed with the introduction of advanced information management tools, e.g. project banks.

The other area not directly related to BIM but more global from the perspective of the projects is project management and control. The design companies are restricted by the very nature of the project-based business, service operations and tender contracting, which all introduce a large share of unpredictability to companies' operations. As a result, the companies have to manage and allocate the resources between the projects ad-hoc, in such a way that most important projects are prioritised.

The general lack of time in projects results in simplistic planning practices (e.g. lack of master schedules), inaccurate scheduling and too general planning of work content. The simplistic scheduling practice and the inability to track the work progress of individual disciplines and designers, which were reported in the case projects, do not help overcoming the unpredictability. This results in the situations when the projects or tasks have to be compromised in favour of more important ones, the tasks have to be transferred to designers that are less occupied and the project organisation has to be extended.

From that point of view such approaches to systematisation of workflow and control as the Last Planner System of Production Control, can give large benefits to design teams. The mentioned system has been implemented in Case project Y and, according to the project manager, gave generally positive results, improving both the manageability of the collaborative design process and mutual understanding of the work process, although it was difficult for designers to adapt to the new method (subsection 5.1.1). The concepts of managing workflow through understanding task dependencies and splitting large project goals into smaller manageable tasks, are suitable for the collaborative BIM process suggested in section 5.3., which seeks to deliver smaller batches of data throughout the design projects. To support project management, software tools for management, production scheduling and control can be utilised by the companies.

Here is a short summary of actions that can be employed by the design companies:

- Moving towards integration of BIM in design process
 - (“Ideally, we should design by modelling”)
- Developing guidelines for designers

- Developing modelling guidelines
- Standardising model quality checking, formats, coordinates, versioning etc.
- Improving BIM expertise
 - Involving the same team in many BIM projects, systematic learning
 - Achieving high level of BIM expertise for designers involved in BIM projects
- Employing data management systems for information exchange
- Improving project management practices
 - Splitting major tasks into smaller subtasks
 - Involving designers in planning and coordination
 - Improving workflow coordination: e.g. Last Planner system
 - Using software tools for project management

5.4. Validation of the results and recommendations for future research

This study is based on the empirical evidence from the case projects and the questionnaire conducted with the case project teams. This approach, while providing in-depth exploratory view of the research subject, has limitations regarding the validity and credibility of results, therefore at least some of the results of this study should be tested and inspected in a better detail in future studies. The same applies to hypotheses that are based on theoretical argumentation but are not broadly tested in this study.

Both case projects that used BIM incorporated the second, general phase of design. It can be interesting to study the implementation of BIM in other design phases, because the importance of the different benefits of BIM and the process of using BIM may differ between design stages. For example, the Case A team has mentioned that BIM was used on the initial stage for evaluating alternatives, while on the general stage the solutions were already ‘fixed’. This may explain why the main benefit of BIM in Case A was clash detection. Cost estimation can play a larger role on the initial stage. The implementation of BIM on the initial and the construction-level stages should be studied in future.

One of the observations made during the research that requires deeper analysis is that the current level of implementation of BIM in design companies may have adverse effect on the timeframe of the design projects. It is possible that in the case projects BIM can result in a bottleneck at the later phase, since neither the technology nor the skills of designers allow fast integration of designs to collaboration model, and because the integration and detection of clashes typically rely on one or two persons. This can also hamper communication between designers, since in traditional process all cross-checking and correction activities are done jointly by designers, on face-to-face meetings.

The evidence that BIM on the level observed in the projects can make projects longer is found both in the swimlane diagrams (long integration and correction phases in projects) and in the questionnaire results (designers have indicated that BIM can make both design corrections and the project in general take more time). A study of a higher number of BIM projects is needed to look more deeply into this problem. At the same time, the process development actions by companies aimed at deeper integration of BIM into the design process discussed in this study might help to mitigate the possible problem.

Another potential topic for future studies relates to perception of BIM. The participants tended to mention various problems related to BIM implementation and interoperability as the current problems, however, stating later that some of these problems have been mostly solved. A large number of problems related to usability of BIM software and certain software functions, resolved in the past, have been also mentioned by designers. This leads to a hypothesis that negative perceptions remain for some time after the problem is solved, in other words there is a lag between the improvement in BIM and the change of perception. This hypothesis can be tested in the future studies.

In general, the current study is based on only four case projects (two BIM projects) in two Finnish companies and may not represent the average state of the industry to the point of time when the research was conducted, especially when talking about the state of industry in other regions. Therefore, there have been limitations in answering the third research question about the current state of BIM and design practice in the AEC sector. Using methodologies other than the case studies and covering larger groups would allow validating the distinct findings made in this research and generalising findings for larger groups with higher level of certainty.

In order to establish more generalised results, questionnaire studies can be conducted similar to the one in the current research project but with higher number of respondents and companies involved. In this study the questionnaires proved to be very beneficial for understanding how professionals perceive the design process, its inherent problems and the impact of BIM, to assess their level of knowledge of BIM and their expectations for better design process and technology.

The triangulation achieved in this study through the use of different types of data and different methods of data collection and analysis provides sufficient credibility of results within the defined scope of the study. The results of the empirical study are supported by the reviewed literature and follow a line of theoretical argumentation.

The future effect of BIM and technology in general on collaborative design in AEC sector needs to be studied more extensively. The needs of industrial collaborative design include activities that are not attributed to designing as an individual task, for

example communication, coordination, planning, control, information handling. Although ICT has provided designers with drawing and engineering tools and information exchange channels, much of the information processes are still paper-based, and management and coordination processes are very basic and are not supported by specialised tools. Although much of the research is focused on construction activities, more efforts are needed in the research on AEC design activities and development of tools and methods for designers.

One of the hypotheses that occurred in this study and was later found in the literature was that designers operate in two basic modes of collaboration:

- close collaboration in a shared design domain, e.g. on a meeting, and
- individual designing, in which contributions are done to areas of expertise, to a large degree independently from other designers.

This observation is mentioned in a study on collaborative design by Kvan (2000). The author describes closely-coupled design, when designers continuously observe and understand each other's moves. At any stage the observer cannot identify a discrete contribution to the design product from one participant or the other. However, Kvan adds that much of the designing is actually loosely-coupled, with each participant contributing to the design within his sphere of expertise. In this case, the experts operate in their own domains on a shared problem, the design moves in discrete steps that can be observed and distinguished from other designers' steps (Kvan, 2000). Potentially, collaborative BIM and co-location can blur the borders between individual and group modes of designing.

The other hypothetical reason why independent, loosely-coupled designing is necessary is that working individually is possibly psychologically easier and could allow better concentration and productivity when more enduring tasks are concerned; this aspect of co-working is, however, out of the scope of this study. There are attempts in other industries to bring two or more designers to perform continuous design activity together, for example, peer programming.

5.5. Exploring the possibility for quantitative research on AEC design activities

The initial goal of this study was to employ quantitative methodology to measure the benefits of BIM and process improvement in infrastructure projects, and possibly calculate the ROI of BIM implementation. However, this goal very soon had to be reconsidered due to the following factors:

- Design companies do not collect enough quantitative data on their activities, because:

- Time of the consultants/designers is the most costly resource in engineering firms
- Management and control are basic and do not employ quantitative methods
- Companies are not willing to spend time of their employees on any activities that do not apparently contribute to the end value, such as data collection and measurement
- Because of the time constraint, researchers who are willing to collect quantitative data in such projects should do so without imposing burden on designers
- The effective and consistent methodology for data collection should be implemented in projects from the beginning until the end, which is difficult considering that a project can take several years

These barriers have shaped the current research, forcing it to re-focus on designers' perceptions rather than on direct measurements and to use predominantly qualitative methodology instead of quantitative. However, the experience obtained in this research and the knowledge of the activities of design firms gained by the end of this study made it possible to formulate the requirements for overcoming those difficulties using some of the software tools available on the market. The recommendations also involve some of the software functionality that does not exist yet but could easily be implemented in some software products. These recommendations were discussed and approved by industry professionals.

Importantly, if a research methodology can be utilised by companies not only for research purposes but for making informed management decisions based on the data, this would increase companies' motivation in conducting the research. Therefore, the development of methods for quantitative analysis of design activity in infrastructure projects can pursue two goals:

- Researchers: realise the potential of software to collect the valuable research data on design process efficiency, planning, collaboration etc., and measure the benefits of BIM in projects
- Project managers and owners: receive up-to-date information about projects based on collected data, in order to support management actions during and after the projects; assess the achievement of performance goals including the success of BIM implementation

A variety of data can be collected by researchers or designers throughout the design project, which includes some of the data that was received during the current research. This data includes meeting notes, recordings (audio/video), schedules, reports on project events (errors, clashes, design changes, delays etc.), description of design alternatives and decisions made and other descriptive information about the projects.

However, the capabilities of manual collection of data in design projects in AEC is limited. It is possible to utilise some of the software products for collecting a larger variety of data, for example by automatic registration of project events and activities that can be used for quantitative analysis. There are at least two types of software products that can be considered for that purpose: project bank software and automatic clash detection software, both of which can be included in BIM solutions.

One of the examples of such software products is VDC Stream developed by Vianova. The difference between ‘traditional’ project banks and VDC Stream is that VDC Stream is a metadata based, and not a folder based, document management system. It can perform automatic versioning, and in addition to downloading the newest revision the users can download any of the older versions of the data. Because of the metadata structure, the project bank saves all actions related to a specific document which means dates, times, persons, revisions of each document downloaded or uploaded. This gives an opportunity to track the workflow in projects. It can be possible to detect project events, for instance, work iterations, changes, delays, especially with the help of data from other sources, and map these events on project timescale.

The second kind of software that could be used to collect data systematically is automatic clash detection software. Such software can record information about the revisions and the identified clashes, which can be used for analysis.

One of the examples is VDC Explorer by Vianova, which is in fact a model integration software with automatic clash detection functionality embedded. The tool is used for creating collaboration models by combining discipline-specific designs, regardless of their native design software, through open data formats such as LandXML and IFC. The clash detection functionality can identify the value of clashes and find the most critical ones (often from thousands of detected clashes). There is also an embedded tool to comment and discuss the clashes. This can allow collecting a variety of data related to clash detection, such as dates, disciplines involved, potential costs, causes, corrections made etc. Textual analysis algorithms and other mathematical and statistical methods can be applied to analyse the collected data.

It is also possible to utilise software to distribute questionnaires or quizzes among designers to study attitudes and perceptions. The format of questionnaire is unsuitable for use in design projects on a regular basis because it takes too much time to fill in. It is possible to distribute single questions or small quizzes from a larger set of questions randomly among designers. This way statistical significance will be achieved without bothering designers too much. Another more sophisticated approach is when specific questions or quizzes are triggered by project events.

The data collection can cover the whole project, and all data can be mapped together on the project timeline (figure 27).

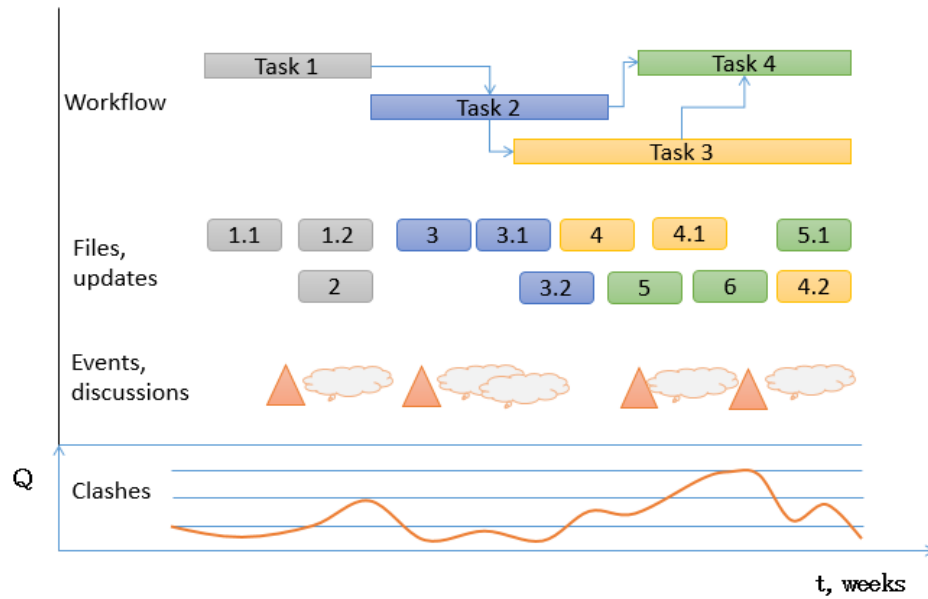


Figure 27: Integration of various types of data on the project timeline.

The chronological analysis of events will reveal problems and causal relationships between them. It will outline the areas where improvement is needed. The received information can support management actions during and after projects.

The potential of software to aid data collection is very promising since software can help overcoming the restrictions related to the cost of designers' time mentioned above. The practical limitations of this particular study, such as the limited timeframe for research, did not allow studying whole ongoing projects, and forced to focus on past case projects. However, the suggestions outlined above can be used in more extensive studies in the future and can help measuring the design performance and the impact of BIM on design process quantitatively.

References

- Aapaoja, A., (2014) 'Enhancing value creation of construction projects through early stakeholder involvement and integration' [Online], University of Oulu [Accessed: 25 August 2014] Available: <<http://herkules oulu.fi/isbn9789526204628/isbn9789526204628.pdf>>
- Aapaoja, A., Herrala, M., Pekuri, A., and Haapasalo, H., (2013) 'The characteristics of and cornerstones for creating integrated teams', *International Journal of Managing Projects in Business*, 6(4): 695-713
- Anumba, C. J., and Kamara, J. M., (2012) 'Concurrent Engineering in Construction', in: Akintoye, A., Goulding, J., and Zawdie, G. (Eds.), *Construction Innovation and Process Improvement*, Oxford, UK: Wiley-Blackwell, 277-292
- Arayici, Y., et al., (2011) 'Technology adoption in the BIM implementation for lean architectural practice', *Automation in Construction*, March 2011, 20(2): 189-195
- Baldwin, A. N, Thorpe, A., and Carter, C. D., (1996) 'The construction alliance and electronic information exchange: A symbolic relationship', in: Langford, D. A., and Retik, A. (Eds.), *International Symposium for the Organization and Management of Construction: Managing Construction Information*, 1996, 3: 23-32
- Ballard, H. G., (2000) 'The Last Planner System of Production Control' [Online], Lean Construction Institute, May 2000 [Accessed: 4 June 2014] Available: <<http://www.leanconstruction.org/media/docs/ballard2000-dissertation.pdf>>
- Barlish, K., and Sullivan, K., (2012) 'How to measure the benefits of BIM – a case study approach', *Automation in Construction*, 2012, 24: 149-15
- Beck, K., et al., (2001) 'Manifesto for Agile Software Development' [Online; published online: 2001; accessed: 10 February 2014] Available: <<http://agilemanifesto.org/>>
- Bergly, G., (2001) 'Productivity and efficiency in the construction industry', *Construction Economics and organisation*, 2nd Nordic conference, Göteborg, 24-25 April 2001, Chalmers University of Technology, 165-172
- Bogus, S. M., Molenaar, K. R., and Diekmann, J. E., (2005) 'Concurrent Engineering Approach to Reducing Design Delivery Time', *Journal of Construction Engineering and Management*, 1 November 2005, 131(11): 1179-1185
- Brown, D. C., (1996) 'Routineness revisited', in: Waldron, M. B., and Waldron, K. J. (Eds.), *Mechanical Design: Theory and Methodology*, NY: Springer, 1996, 195-208
- Brown, D. C., and Chandrasekaran, B., (1985) 'Expert Systems for a class of mechanical design activity, in: Gero, J. S. (Ed.), *Knowledge Engineering in Computer-Aided Design*, 1985, 259-276
- Building SMART Finland, (n.d.) 'Building SMART Finland' [Online, accessed: 7 November 2014] Available: <<http://www.en.buildingsmart.kotisivukone.com/>>
- Coates, P., et al., (2010) 'The key performance indicators of the BIM implementation process' [online], in: *The International Conference on Computing in Civil and Building Engineering*, 30 June - 2 July 2010, Nottingham, UK [Published online: 17 August 2010; accessed: 11 February 2013] Available at University of Salford Institutional Repository: <<http://usir.salford.ac.uk/9551/>>

Coyne, R. D., Rosenman, M. A., Radford, A. D., and Gero, J. S., (1987) 'Knowledge-based computer-aided architectural design', in: Gero, J. S. (Ed.), *Knowledge Engineering in Computer-Aided Design*, North-Holland, Amsterdam, 57-81

Damielo, R., (2011) 'The Basics of Process Mapping', 2nd Ed., CRC Press

Davern, M. J., and Kauffman, R. J., (2000) 'Discovering potential and realizing value from information technology investments' [online], *Journal of Management Information Systems - Special issue: Impacts of information technology investment on organizational performance*, M. E. Sharpe, Inc., Armonk, NY, USA, March 2000, 16(4): 121-143 [Abstract in the ACM Digital Library, ref. no. 1189433; accessed: 3.6.2014] Available: <<http://dl.acm.org/citation.cfm?id=1189433>>

De la Garza, J. M., Alcantara, P., Jr., Kapoor, M. and Ramesh, P. S., (1994) 'Value of Concurrent Engineering for A/E/C Industry', *Journal of Management in Engineering*, May/June 1994, 10(3): 46-55

Eastman et al., C., Teicholz, P., Sacks, R., and Liston, K., (2008) 'BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors', John Wiley & Sons, Inc., Hoboken, NJ, USA

Eppinger, S. D., (2001) 'Innovation at the Speed of Information', *Harvard Business Review*, January 2001, 149-158

Fulford, R. and Standing, C., (2014) 'Construction industry productivity and the potential for collaborative practice', *International Journal of Project Management* 32(2): 315-326

Gallaher, M. P., O'Connor, A. C., Dettbarn, J. L., Jr., and Gilday, L. T., (2004) 'Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry', August 2004

Gann, D., and Salter, A., (1998) 'Learning and innovation management in project-based, service-enhanced firms', *International Journal of Innovation Management*, 2(4): 431-454

Gero, J. S., (1990) 'Design prototypes: a knowledge representation schema for design', *AI Magazine*, winter 1990, 11(4): 27-36

Gero, J. S., and Kannengeisser, U., (2004) 'The situated function-behaviour-structure framework', *Design Studies*, July 2004, 25(4): 373-391

Hicks, B. J., (2007) 'Lean information management: Understanding and eliminating waste', *International Journal of Information Management*, August 2007, 27(4): 233-249

InfraBIM, (n.d.) 'InfraBIM, Inframallintamisen Yhteistyöfoorumi' ('InfraBIM, Infrastructure Modeling Cooperation Forum' - Finnish) [Online, accessed: 7 November 2011] Available: <<http://www.infrabim.fi/>>

Kang, J. H., Anderson, S. D., and Clayton, M. J., (2007) 'Empirical Study on the Merit of Web-Based 4D Visualization in Collaborative Construction Planning and Scheduling', *Journal of Construction Engineering and Management*, 133(6): 447-461

Karlsson, K., and Åhlström, P., (1996) 'The difficult path to lean product development', *Journal of Product Innovation Management*, July 1996, 13(4): 283-295

Khanzode, A., (2012) 'Making the integrated Big Room better' [Online], DPR Construction, October 2012 [Published online: 23 October 2012; accessed: 12 February 2013] Available at: <<https://www.dpr.com/media/technical-papers/making-the-integrated-big-room-better>>

- Kiviniemi, A., (2005) 'Requirements Management Interface to Building Product Models' [Online], CIFE Technical Report 161, March 2005, Stanford University [Published online: 3 March 2005; accessed: 11 February 2013] Available: <<http://cife.stanford.edu/node/185>>
- Kleinsmann, M., (2008) 'Barriers and enablers for creating shared understanding in collaborative design projects', *Design Studies*, July 2008, 29(4): 20-32
- Kleinsmann, M., (2010) 'Understanding the complexity of knowledge integration in collaborative new product development teams: A case study', *Journal of Engineering and Technology Management*, 2010, 27: 20-32
- Krishnan, V., Eppinger, S. D., and Whitney, D. E., (1995) 'Accelerating product development by the exchange of preliminary product design information', *Journal of Mechanical Design*, December 1995, 117: 491-498
- Kvan, T., (2000) 'Collaborative design: what is it?' *Automation in Construction*, 2000, 9: 409-415
- Lædre, O. and Haugen, T. I., (2001) 'Use of project partnering in construction: examining the effect of project integration and target pricing in three pilot projects', *Construction Economics and organisation*, 2nd Nordic conference, Chalmers University of Technology, Göteborg, 24-25 April 2001, 139-146
- Larman, C., (2004) *Agile and Iterative Development: A Manager's Guide*, Agile software development series, Boston: Pearson Education
- Licker, J. K., Sobek, D. K., Ward, A. C., and Cristiano, J. J., (1996) 'Involving suppliers in product development in the United States and Japan: Evidence for set-based concurrent engineering', *IEEE Transactions on Engineering Management*, May 1996, 43(2): 165-178
- Mahmood, M. A., and Mann, G. J., (1993) 'Measuring the organizational impact of information technology investment: an exploratory study' [Online], *Journal of Management Information Systems - Special section: Realizing value from information technology investment*, M. E. Sharpe, Inc., Armonk, NY, USA, June 1993, 10(1): 97-122 [Abstract in the ACM Digital Library, ref. no. 1189687; accessed: 3.6.2014] Available: <<http://dl.acm.org/citation.cfm?id=1189687>>
- Maier, A.M., Eckert, C.M., and Clarkson, P.J., (2005) 'A meta-model for communication in engineering design', *CoDesign: International Journal of CoCreation in Design and the Arts*, December 2005, 1(4): 243-254
- Matthews, O., and Howell, G. A., (2013) 'Integrated project delivery an example of relational contracting', *Lean Construction Journal*, April 2005, 2(1): 46-61
- Moeller, S., (2010) 'Characteristics of services – a new approach uncovers their value', *Journal of Services Marketing*, 2010, 24(5): 359-368
- Mom, M., and Hsieh, S.-H., (2012) 'Toward performance assessment of BIM technology implementation' [Online], in: Telichenko, V., Volkov, A. and Bilchuk, I. (Eds.), 14th International Conference on Computing in Civil and Building Engineering, Moscow, 27-29 June 2012 [Published online: 17 August 2010; accessed: 11 February 2013] Available at: <http://www.icccbe.ru/paper_long/0187paper_long.pdf>
- Morgan, J. M., and Liker, J. K., (2006) 'The Toyota product Development Systems: Integrating people, process and technology', Taylor & Francis, Business & Economics, 2006

- Ohno, T., (1998), 'Toyota Production System: Beyond Large-Scale Production', Productivity Press, March 1998
- Parasuraman, A., Zeithaml, V. A., and Berry, L. L., (1985) 'A conceptual model of service quality and its implications for future research', *Journal of Marketing*, Autumn 1985, 49(4): 41-50
- Parrish, K., Wong, J.-M., Tommelein, I.D., and Stojadinovic, B., (2007) 'Communication and process simulation of set-based design for concrete reinforcement', in: *Simulation Conference*, winter 2007, 9-12 December 2007, Washington, DC, 2057-2065
- Parsons, M., Singer, D., and Sauter, J., (1999) 'A Hybrid Agent Approach For Set-Based Conceptual Ship Design', *International conference on Computer Applications in Shipbuilding*, Cambridge, 1999, 7-11
- Pei, E., Campbell, I., and Evans, M. A., (2009) 'Building a Common Ground – The Use of Design Representation Cards for Enhancing Collaboration between Industrial Designers and Engineering Designers', in: *Undisciplined! Design Research Society Conference 2008*, Sheffield Hallam University, Sheffield, UK, 16-19 July 2008
- Plume, J., and Mitchell, J., (2007), 'Collaborative design using a shared IFC building model - Learning from experience', *Automation in Construction*, 16: 28-36
- Poerschke, U., Holland, R., Messner, J. I., and Pihlak, M., (2010) 'BIM collaboration across six disciplines' [Online], in: Tizani, W. (Ed.), *Proceedings of the International Conference on Computing in Civil and Building Engineering*, 2010 [Accessed: 18.11.2014] Available: <<http://www.engineering.nottingham.ac.uk/iccbe/proceedings/pdf/pf288.pdf>>
- Royce, W., (1970) 'Managing the Development of Large Software Systems', *Proceedings of IEEE WESCON*, August 1970, 26: 1-9
- Sattineni, A., and Bradford, R. H., II, (2011) 'Estimating with BIM: a survey of us construction companies' [Online], *Proceedings of the 28th ISARC*, Seoul, Korea, International Association for Automation and Robotics in Construction, 564-569 [Online proceedings database; accessed: 3.6.2014] Available: <<http://www.iaarc.org/publications/fulltext/S16-6.pdf>>
- Schwaber, K., and Sutherland, J., (2013) 'The Scrum Guide. The Definitive Guide to Scrum: The Rules of the Game' [Online], *Scrum.org*, July 2013 [Accessed: 11 June 2013] Available at: <<https://www.scrum.org/Portals/0/Documents/Scrum%20Guides/2013/Scrum-Guide.pdf#zoom=100>>
- Singh, V., Gu, N., and Wang, X., (2011) 'A theoretical framework of a BIM-based multi-disciplinary collaboration platform', *Automation in Construction*, 20: 134-144
- Succar, B., (2009) 'Building information modelling framework: A research and delivery foundation for industry stakeholders', *Automation in Construction*, May 2009, 18(3): 357-375
- Succar, B., Sher, W., and Williams, A., (2012) 'Measuring BIM performance: Five metrics' [Online], *Architectural Engineering and Design Management*, 2012, 8: 120-142, [Published online: 26 March 2012; accessed: 10 February 2014] Available: <<http://www.tandfonline.com/doi/abs/10.1080/17452007.2012.659506>>
- Wegner, D. M., (1995) 'A Computer Network Model of Human Transactive Memory', *Social Cognition*, 13(3): 319-339

Weill, P., (1992) 'The relationship between investment in information technology and firm performance: A study of the valve manufacturing sector' [Online], Information Systems Research, December 1992, 3(4): 307-333 [Abstract, published online: 1 December1992; accessed: 3 June 2014] Available: < <http://dx.doi.org/10.1287/isre.3.4.307>>

Wilson, T., Wiebe, J., and Hoffmann, P., (2008) 'Recognizing contextual polarity: An exploration of features for phrase-level sentiment analysis' [Online], Computational Linguistics, 35(3) [Accessed: 16.6.2014] Available: <<http://www.mitpressjournals.org/doi/pdf/10.1162/coli.08-012-R1-06-90>>

Womack, J. P., Jones, D. T., (2003) 'Lean Thinking: Banish Waste and Create Wealth in Your Corporation', NY: Free Press

Appendix: The questionnaire form

Collaborative design practices and BIM: survey for project teams in infrastructure sector

In: "Measuring the benefits of Building Information Modelling (BIM) and process improvement for collaborative design in infrastructure projects"

Alexander Gerbov, Vishal Singh, Maila Suvanto and Heikki Halttula,
Aalto University and Vianova Systems Finland Oy

About the survey:

In this survey you will be asked about your professional background and your experiences of collaboration and software use. It will prepare the ground for our workshop discussion. The survey will include 11 questions and will last about 10 minutes.

Note: the information provided by you for the research is confidential. Personal identifications or information that might constitute personal or commercial secret may be asked only for research purposes, and will never be disclosed. The published results will be detached from any information that could help to connect them with personal or companies' identities.

1. How much do you know about BIM?

Please, circle the correct answer (1-5) from the relevant column

Example: ①

I have never worked with BIM and...

I have worked with BIM and...

1. I have never heard about BIM
2. I have little knowledge about BIM
3. I have general knowledge about BIM
4. I have somewhat good knowledge about BIM
5. I have good knowledge about BIM

1. I have little knowledge about BIM
2. I have general knowledge about BIM
3. I have somewhat good knowledge about BIM
4. I have good knowledge about BIM
5. I have deep knowledge about BIM

2. How much do you want to work in projects that use BIM in future?

I don't want to 1 2 3 4 5 6 7 I want very much

3. How much do you agree with the statement: "using BIM gives clear and strong benefits to designers and engineers"?

Do not agree 1 2 3 4 5 6 7 Strongly agree
 0 - I am not familiar with the benefits of BIM

4. According to your understanding, what are the most important features of BIM?

Please, name 1-3 most important features of BIM that you know, or have heard of

5. How well do you know about the features of BIM, in general?

Very little 1 2 3 4 5 6 7 Very well

0 - I do not know anything about features of BIM

6. What are the problems that you face most often when working with other designers and engineers?

Please, name 1-3 most usual problems related to working with other designers and engineers

7. In your opinion, how efficient is the way designers work in the infrastructure projects?

Very inefficient 1 2 3 4 5 6 7 Very efficient

8. How satisfied are you with the communication in the project teams that you work in?
 Not satisfied 1 2 3 4 5 6 7 Very satisfied

9. According to what you know, please rate the effect that BIM has on the following parameters:

Circle the value that, in your opinion, represents how BIM affects the following parameters.

N – I do not know at all /never heard

-3 – Very negative

3 – Very positive

a. Awareness of project's state and actions of other designers	<u>N</u> -3 -2 -1 0 1 2 3
b. Searching and finding the right data	<u>N</u> -3 -2 -1 0 1 2 3
c. Ease and joy of working	<u>N</u> -3 -2 -1 0 1 2 3
d. Project delivery time	<u>N</u> -3 -2 -1 0 1 2 3
e. Time required for design changes and additions	<u>N</u> -3 -2 -1 0 1 2 3
f. Collaboration and information exchange	<u>N</u> -3 -2 -1 0 1 2 3
g. Visual exploration of design	<u>N</u> -3 -2 -1 0 1 2 3
h. Quality of design	<u>N</u> -3 -2 -1 0 1 2 3
i. Simulation, calculation and analysis	<u>N</u> -3 -2 -1 0 1 2 3
j. Clash and error detection	<u>N</u> -3 -2 -1 0 1 2 3

10. Your educational degree

a. Bachelor b. Master c. Licentiate d. Ph.D.

e. Other, please specify: _____

11. How many years have you worked in your field?

a. 0 - 1 b. 1 - 3 c. 3 - 5 d. 5 - 10 e. 10 - 20 f. > 20

Thank you!